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TAPERED ROLLER BEARING DEVELOPMENT FOR AIRCRAFT TURBINE ENGINES

THE TIMKEN COMPANY
1835 DUEBER AVENUE S.W.
CANTON, OHIO 44706

DECEMBER 1977

TECHNICAL REPORT AFAPL-TR-77-83
INTERIM REPORT FOR PERIOD OCTOBER 1976 — OCTOBER 1977

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AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This interim report was submitted by the Timken Company, under Contract F33615-76-C-2019. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 304806, and Work Unit 30480684, with Lt. R. L. Gissel (AFAPL/SFL) as project engineer. Mr. Peter S. Orvos of the Timken Company was technically responsible for the work.

This report has been reviewed by the Information Office (ASD/OIP), and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Evaluation tests at speeds to 3.5 million DN were conducted on seven cage designs for high speed tapered roller bearings. These designs were comprised of three geometric and material options and two surface coatings. The race guided Z-type machined from AISI 4340 steel and silver plated proved to be the best design. Performance tests were conducted on both this design and a roller guided cage. The parametric investigation included effects of speed, lubricant viscosity, load, lubricant distribution and cage design on bearing

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20. Abstract (Continued)

heat generation (torque). Additionally, oil off tests were run to simulate oil supply cessation. Two sets of bearings operating at 1.5 million DN under 2000 lbf. thrust load survived for greater than one minute without impairment of rotational capabilities.

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TABLE OF CONTENTS

ILLUSTRATIONS

LIST OF TABLES

SECTION I
INTRODUCTION

This report documents the cage evaluation and bearing performance test phases of the program, "Tapered Roller Bearing Development for Aircraft Turbine Engines." Previous work by The Timken Company under the sponsorship of the Air Force Aero-Propulsion Laboratory (ref. 1) demonstrated the capability of a tapered roller bearing operating at speeds of 3.5 million DN. It had shown that with additional development of the cage (component that separates rollers and retains them as a unit to a race), tapered roller bearings have the potential for meeting the future speed and load requirements of aircraft turbine engines.

The first interim report (ref. 2) published under this contract presented the structural analysis using finite element methods on various cage designs. This represents Task I of the overall program. Included in this study were both roller and race guided types with geometric and material variations. In summary this investigation concluded:

1) The "L-type," stamped from a low carbon sheet steel, representative of standard tapered roller bearing cage design and material, has insufficient tensile strength for higher speed ranges studied.

2) Modifying this design by extending the large end ring perpendicular to the bearing centerline to form the "S-type" does not significantly improve strength.

3) Alternate materials of higher strength for either of the two previous cage designs could produce a satisfactory design. This would be contingent upon being able to machine and stamp these without developing stress risers.

4) For the higher speed ranges studied, the "Z-type" is the superior design. It is a completely machined, race guided design. Inertia induced stresses and deformation are the lowest level of all designs analyzed.

The cage evaluation tests are Task II of this development. These tests provide a means for verifying the analytical studies. The bearing performance tests, Task III, represent an enhancement of the "state of the art" of high speed tapered roller bearing operation. Included in this phase is torque and heat generation as a function of speed, load, oil distribution and cage design. Additionally, oil off tests were run to bearing damage.

Section II describes the bearings and cages tested. The test rig is described in Section III. The procedures used and results of the developmental and performance tests are presented in Sections IV and V, respectively. Conclusions and recommendations from the results of these tests are given in Section VI.

SECTION II

TEST BEARINGS

2.1 Cup, Cone and Rollers

A total of thirty L521900 series Timken tapered roller bearing assemblies modified for high speed and identified as the XC1933 were used for the developmental and performance tests. Fifteen of these assemblies had been manufactured in 1973 under the previous contract (ref. 1). The remaining fifteen had been manufactured in 1976 for this current program. Both groups of bearings were made from the same heat of CEVM CBS-1000M high temperature bearing steel. Its chemical composition is shown on Table 1, "Test Bearing Specifications."

The internal geometry for these two lots of bearings is identical. The included cup (outer race) angle is 29° 20' and the included roller angle 1° 36'. Roller slant length is 0.6001 in. (15.243 mm) and the spherical end radius is 75 to 80 percent of the apex length. The bearings with the roller guided cage have 39 rollers and the race guided type have 37 rollers. The thrust ratings for these bearings are 3140 and 3030 lbf. (14 000 and 13 500 N), respectively. The rating differences reflect the difference in number of rollers.

The assembly drawing of the XC1933CE-XC1933DC roller guided cage bearing is shown on Figure 1. The race guided type, XC1933CG-XC1933DD assembly is shown on Figure 2. Both bearings have a 4.25 in. (107.95 mm) bore and a 5.75 in. (146.05 mm) outside diameter.

TABLE 1

TEST BEARING SPECIFICATIONS

Chemical Composition Ranges of Cup, Cone and Roller Material - CBS-1000M

C	Mn	P	S	Si	Cr
.12/.16	.40/.60	.025 Max.	.025 Max.	.40/.60	.90/1.20

Ni	Mo	Co	Al	V
2.75/3.25	4.75/5.25	---	---	.25/.50

Manufacturing

Dimensional Tolerances - Timken Class 2
Additional Requirements - Helicopter Transmission Code
Handling - Traceability on All Components

Surface Finish (Measured A.A. - Microinches)
Cup, Cone and Rollers

	XC1933CE - XC1933DD	XC1933CG - XC1933DD
Pretest Surface Condition	Nital Etched	As Ground or Honed
Cup Race	6 - 7	6 - 7
Cone Race	8	4 - 6
Cone Rib Face	10	7 - 10
Roller Body	4.5 - 5.5	4.5 - 5.5
Roller Spherical End	4 - 7	4 - 6

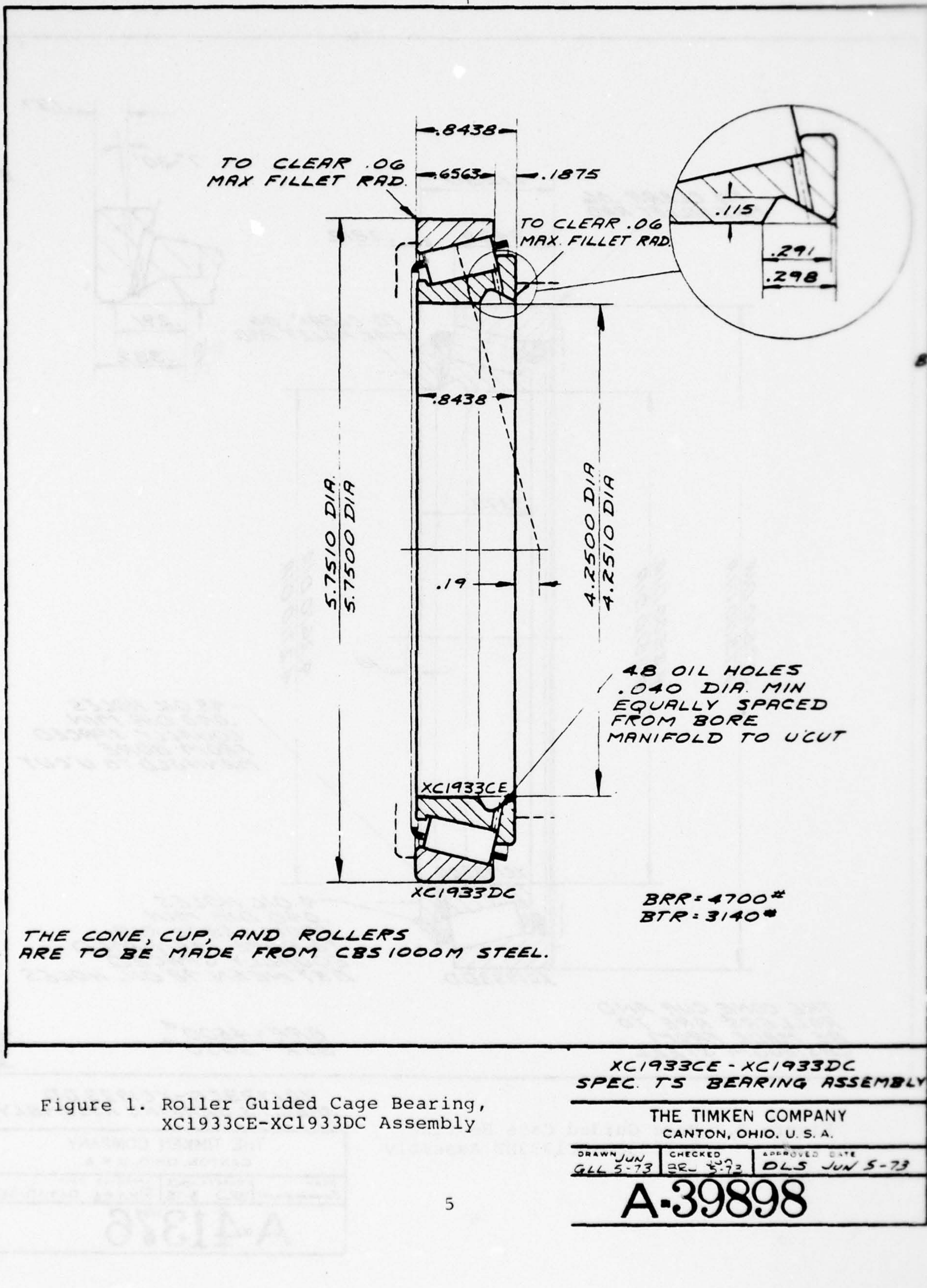


Figure 1. Roller Guided Cage Bearing, XC1933CE-XC1933DC Assembly

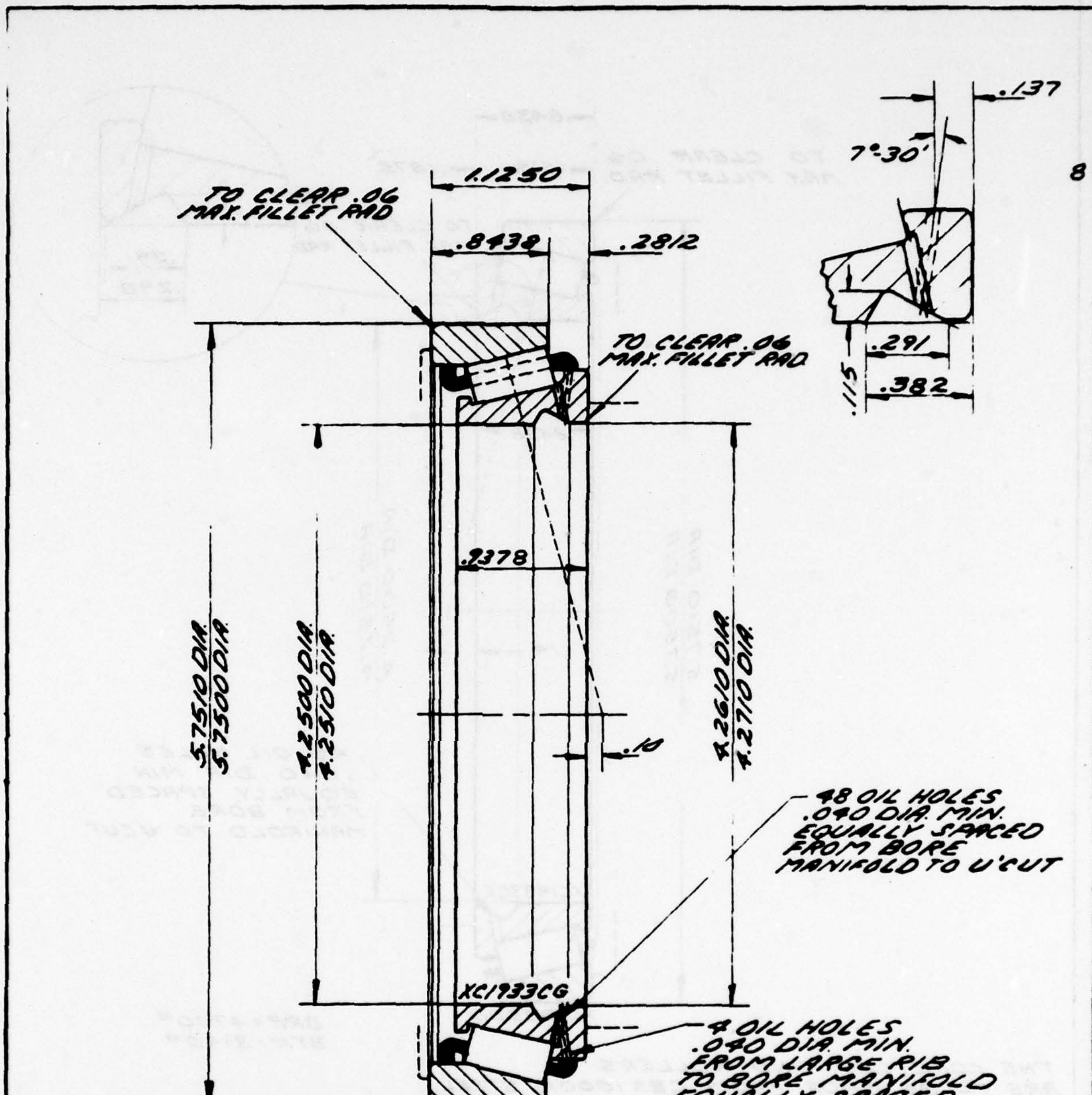


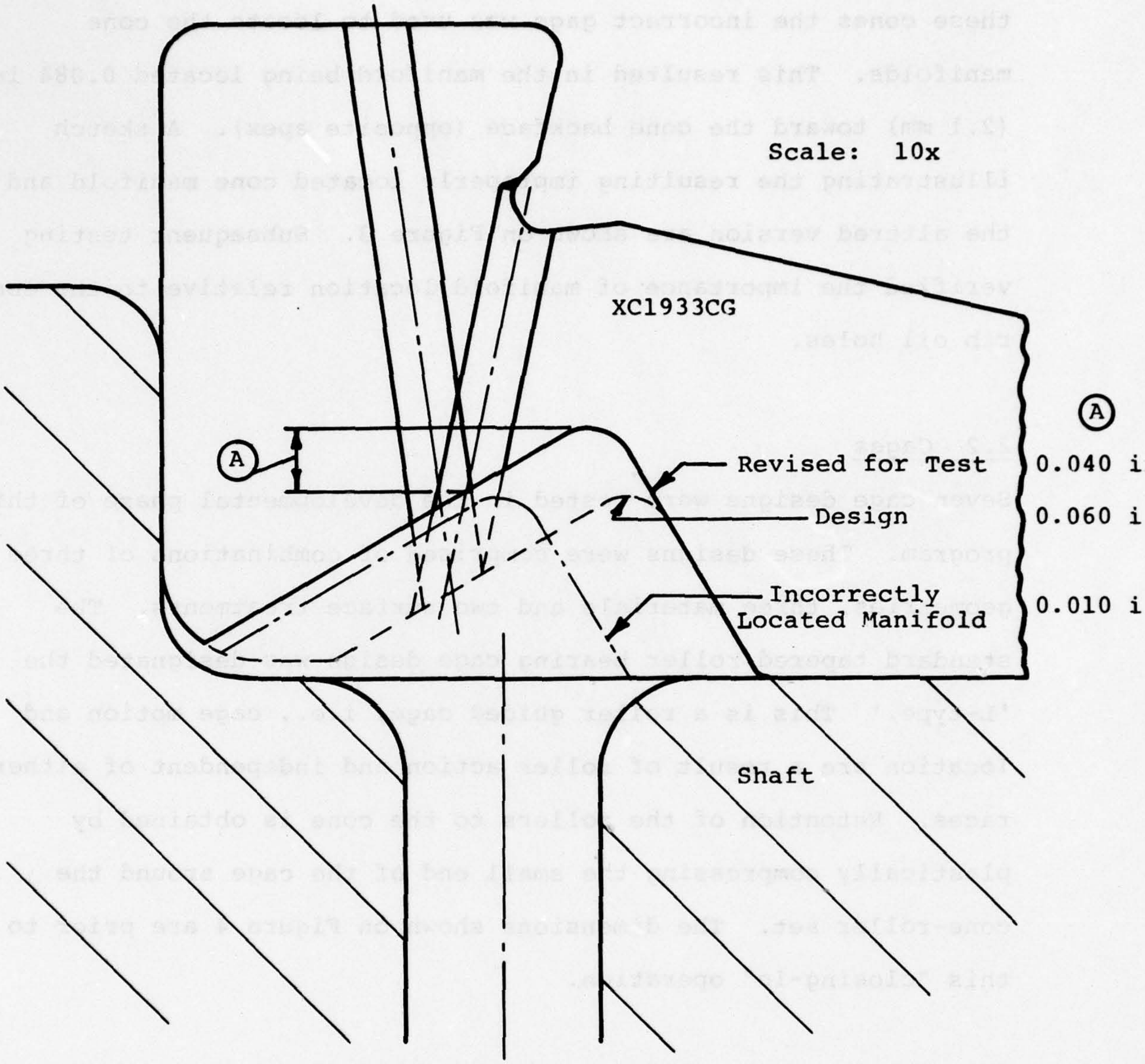
Figure 2. Race Guided Cage Bearing, XC1933CG-XC1933DD Assembly

To provide a pilot for the race guided design the cup and cone were extended axially. During the manufacturing of a portion of these cones the incorrect gage was used to locate the cone manifolds. This resulted in the manifold being located 0.084 in. (2.1 mm) toward the cone backface (opposite apex). A sketch illustrating the resulting improperly located cone manifold and the altered version are shown on Figure 3. Subsequent testing verified the importance of manifold location relative to the cone rib oil holes.

2.2 Cages

Seven cage designs were tested in the developmental phase of this program. These designs were comprised of combinations of three geometries, three materials and two surface treatments. The standard tapered roller bearing cage design was designated the 'L-type.' This is a roller guided cage, i.e., cage motion and location are a result of roller action and independent of either races. Retention of the rollers to the cone is obtained by plastically compressing the small end of the cage around the cone-roller set. The dimensions shown on Figure 4 are prior to this "closing-in" operation.

The S-type cage is shown on Figure 5. It also is a roller guided design. The cage-roller conjunction and its assembly methods are identical to the L-type. The design difference is the extension and shape of the large end ring.



NOTE: A Dimension is radial distance from intersection of rib oil hole centerline to manifold.

Figure 3. Three Manifold Profiles Tested on XC1933CG Cone

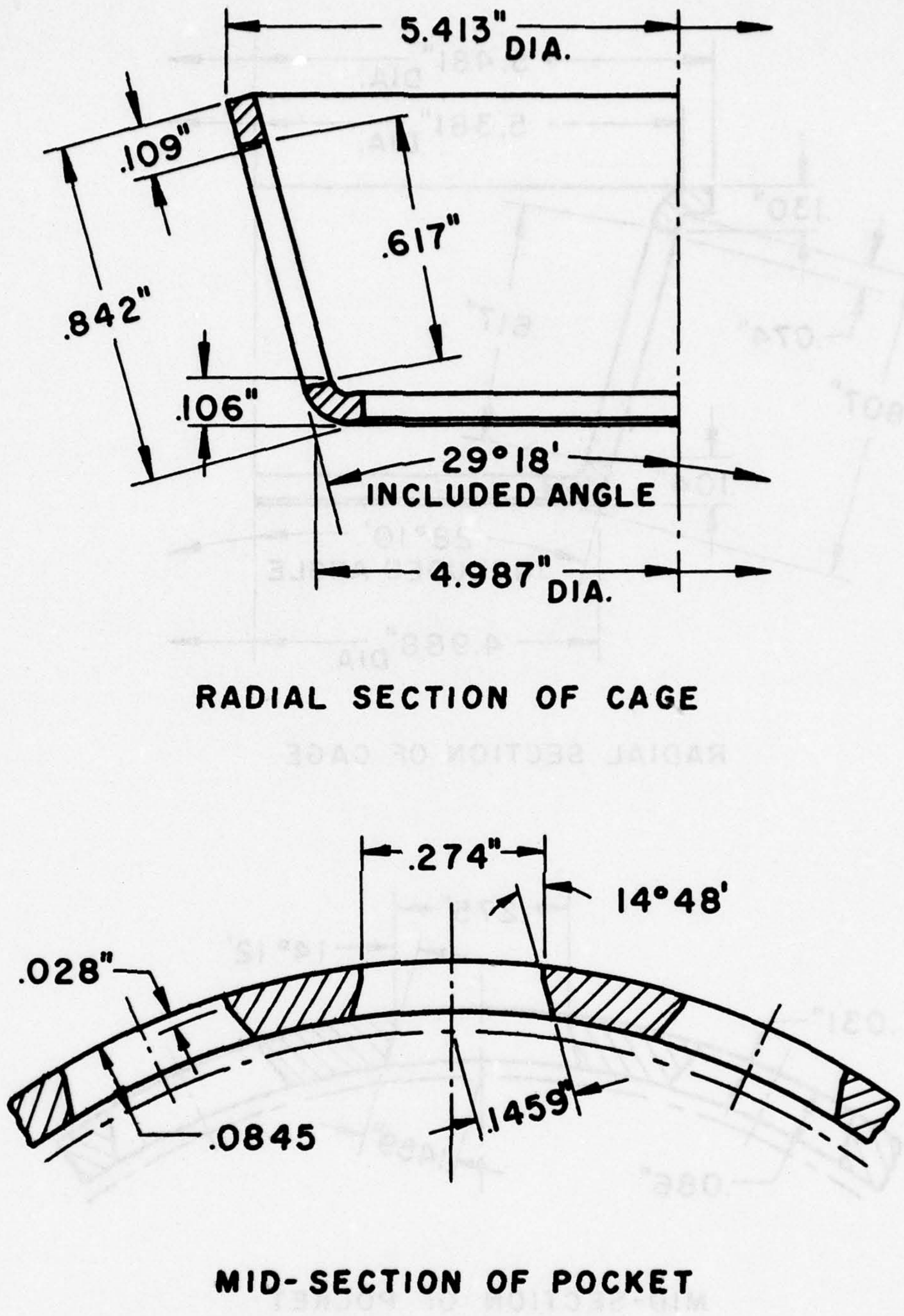
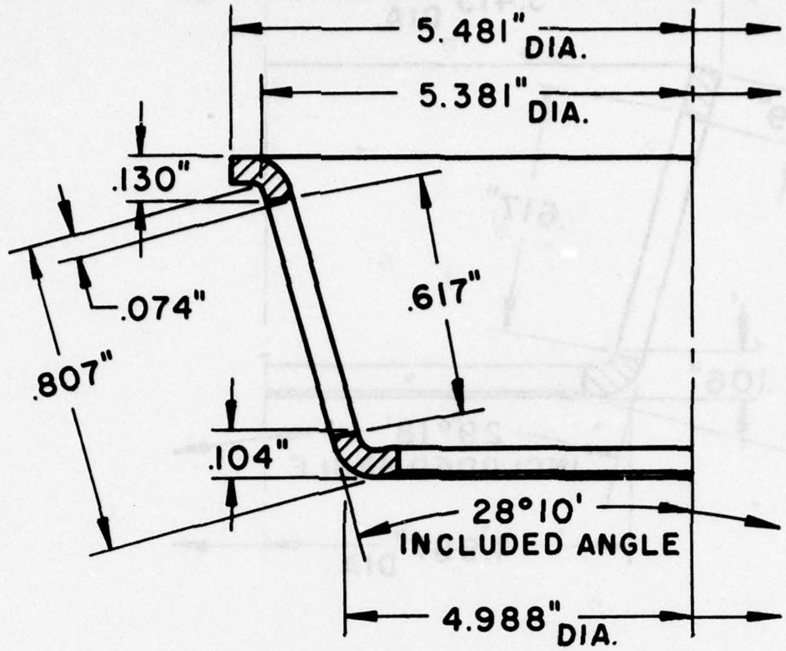


Figure 4. L-Type Cage, 39 Pockets



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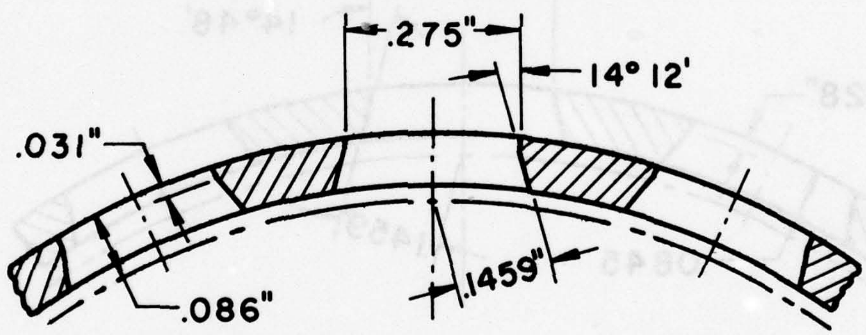


MID-SECTION OF POCKET

Figure 5. S-Type Cage, 39 Pockets

The race guided Z-type cage is shown on Figure 6. In this design orbital cage motion and location are affected by both races and rollers. The cage pockets are larger than the rollers. To retain the rollers to the cone, slots were milled in the bridge O.D.'s. The walls of the bridge could then be plastically deflected outward to lock the rollers into the cage pocket. However, in this program the final step was omitted in order that the cages could be reused.

The two surface treatments used in test were zinc phosphate coating and silver plating. All silver plating conformed to Federal Specification QQ-S-365b, Type II, Grade B. A third treatment was investigated but not run in a bearing test. Two, L-type roller guided cages were "Ferritic-Nitrocarburized" by Nemo Heat Treatments Limited of England. During the closing-in operation the bridges fractured due to the formation of a brittle layer as a result of the process.

Listed below are cage descriptions listed in test sequence.

XC1933AB

Roller guided, L-type cage fabricated by a combined machining and stamping process. Geometrically resembles standard tapered roller bearing cage but is made of AISI 4340 steel. Tested with both surface treatments, zinc phosphating and silver plating.

L521906

Standard tapered roller bearing cage completely stamped from hot rolled AISI 1008-1010 sheet steel. Surface treatment was silver plating.

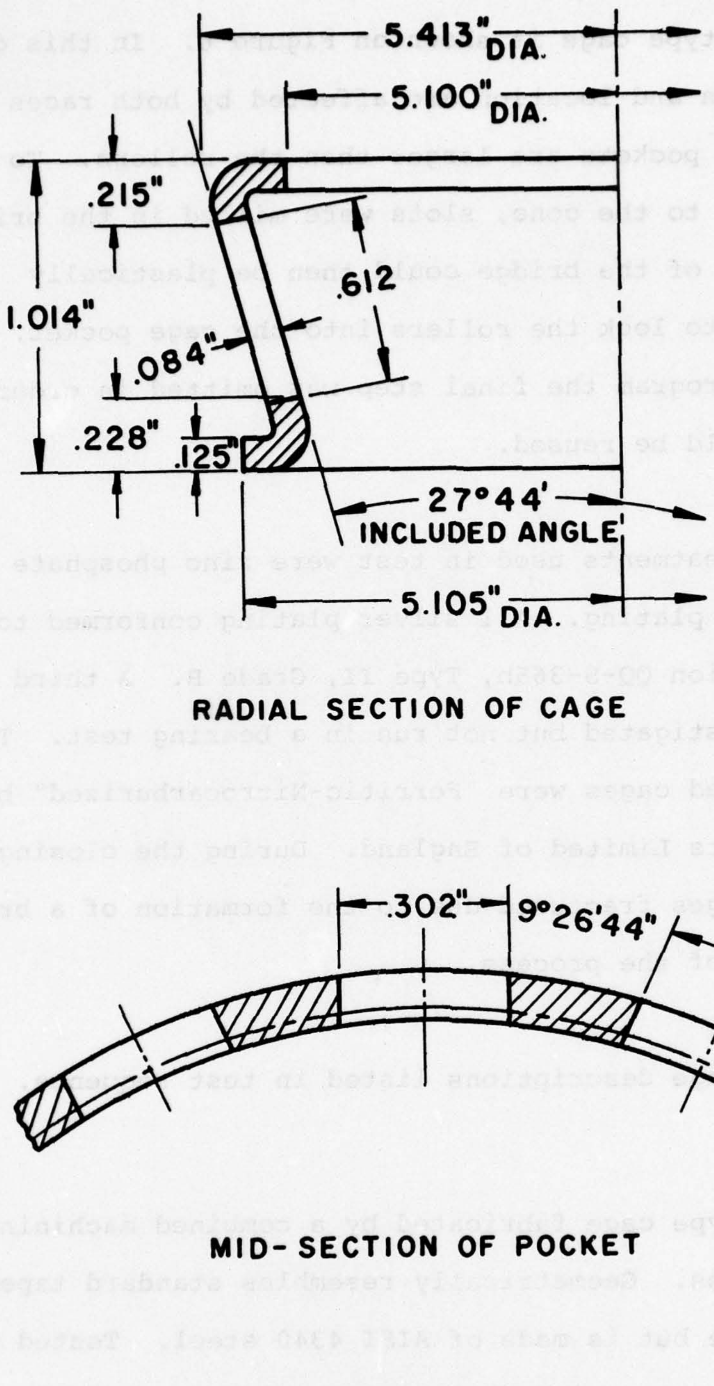


Figure 6. Z-Type Cage, 37 Pockets

XC1933AC

Roller guided, S-type cage completely stamped from AISI 1010 sheet steel. Surface treatment was silver plating.

XC1933AE

Roller guided, S-type cage fabricated by a combined machining and stamping process from AISI 4340 steel. Geometrically similar to XC1933AC cage. Surface treatment was silver plating.

XC1933AG

Roller guided, L-type cage completely stamped from 5052-H32 aluminum alloy sheet. The surface treatment was silver plating with modification for aluminum.

XC1933AF

Race guided, Z-type cage completely machined from AISI 4340 steel. The bench diametrical clearances for the cage piloting surfaces was 0.015 in. (0.38 mm) and 0.010 in. (0.25 mm) when the cone was pressed on the shaft. Initial test runs indicated wear occurring at the I.D. of the cage adjacent to the large rib.

This interference was eliminated by grinding 0.020 in. (0.51 mm) off the I.D. of the cage between the piloting surfaces eliminating this wear problem. Surface treatment was silver plating.

SECTION III

TEST RIG

A Timken Company High Speed Test Machine was used for all testing in this program. The machine is capable of testing the XC1933 series bearing (107.95 mm bore) at speeds up to 3.5×10^6 DN under thrust loads up to 6000 lbf. (26 700 N). The following figures show specific details of the machine and instrumentation.

Figure 7 - *Overall View of Test Machine, Right Side*

Figure 8 - Overall View of Test Machine, Left Side

Figure 9 - Control Panel for Test Machine

A block diagram of the high speed test machine is shown in Figure 10. Its operation is described as follows:

The drive system capability is 33,500 RPM by use of a 125 H.P. (93.2 kW) variable speed D.C. electric motor (1) coupled to a 15.225:1 ratio transmission (2).

The bearing housing (3) is mounted on a Lebow Model 2230-101 torque table (4) with 1,000 lb·in (113 N·m) rated capacity, torque values being recorded on a Fluke Summa II data logger.

The bearing lubrication system has a stainless steel heat exchanger (5) capable of handling 400°F (204°C) oil. Inlet oil flow is measured by turbine type oil flow meters (6) capable of 2-15 GPM (8-57 L/min.) flow at 500°F (260°C) while flow control valves allow for testing at varying flow rates. The oil flow meters generate millivolt signals which are transmitted to the aforementioned data logger.

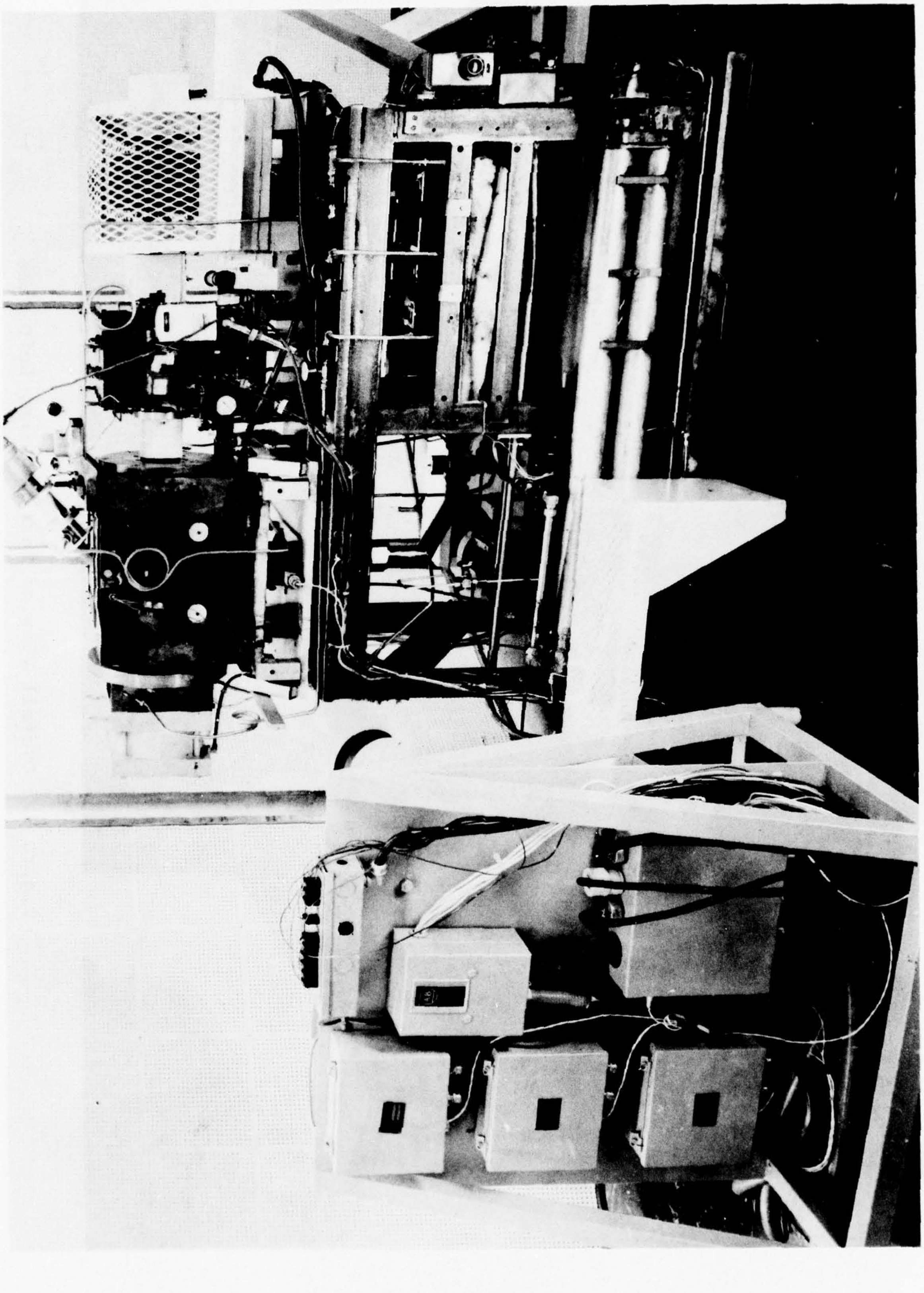


Figure 7. Overall View of Test Machine, Right Side

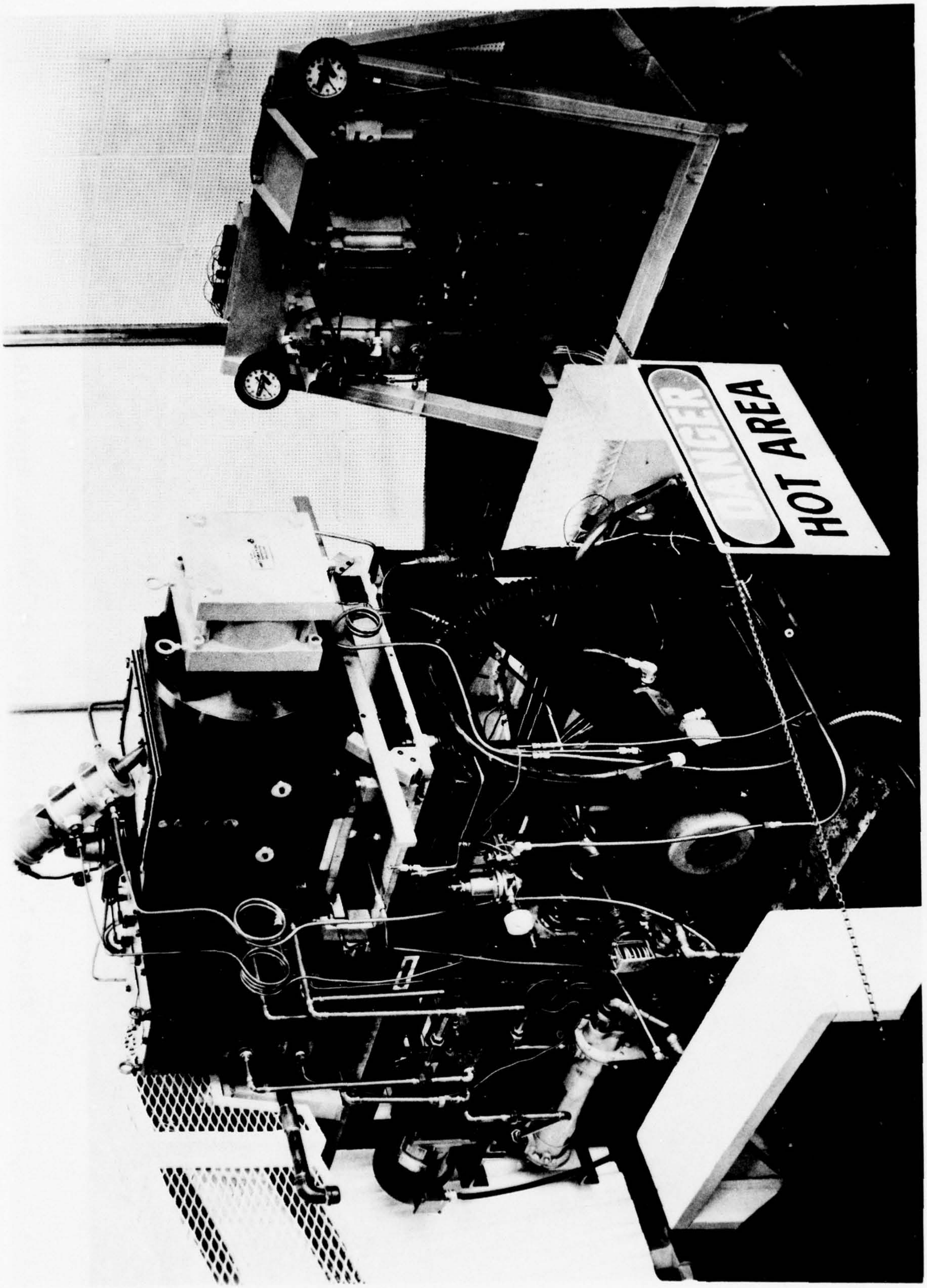


Figure 8. Overall View of Test Machine, Left Side

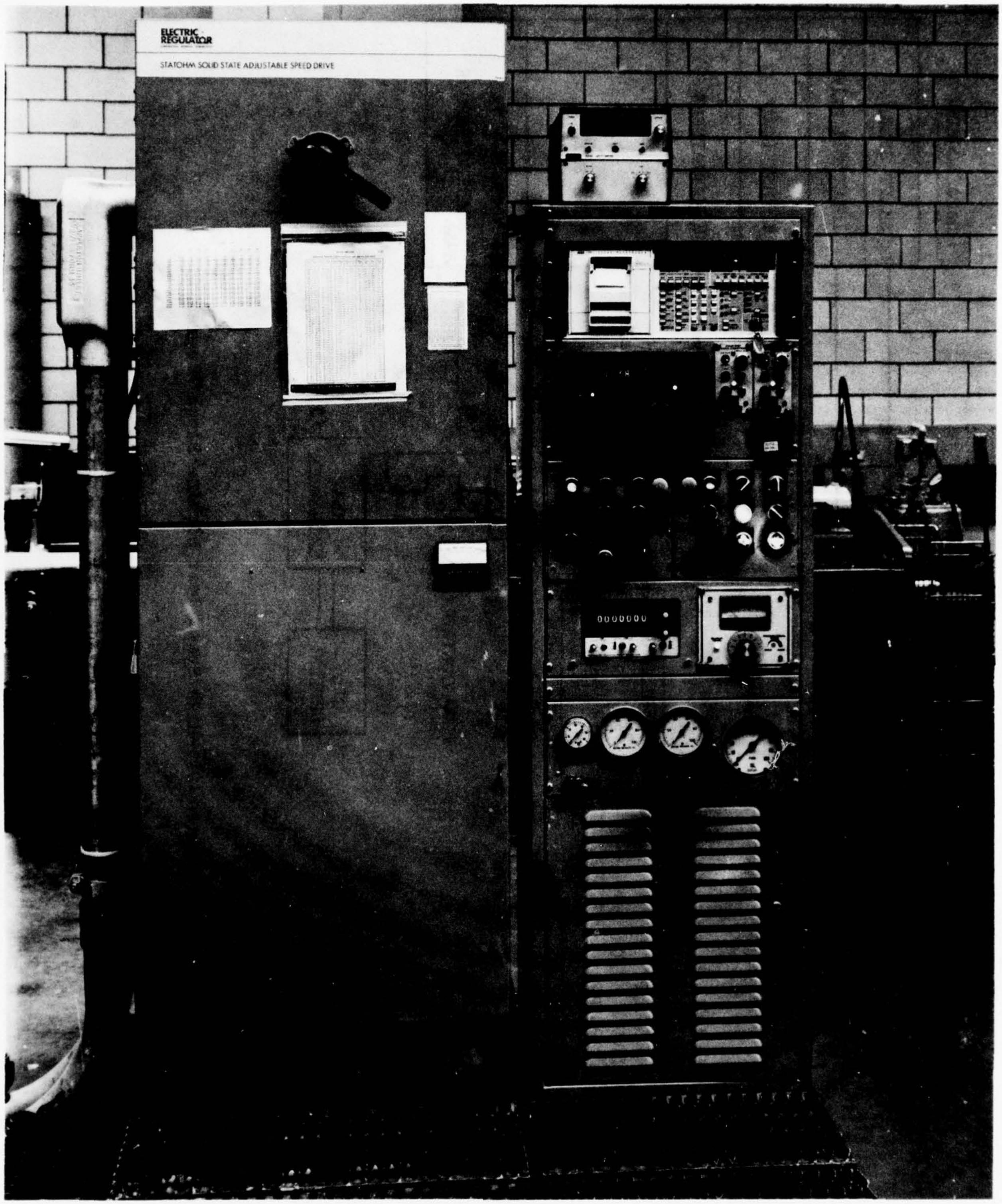


Figure 9. Control Panel For Test Machine

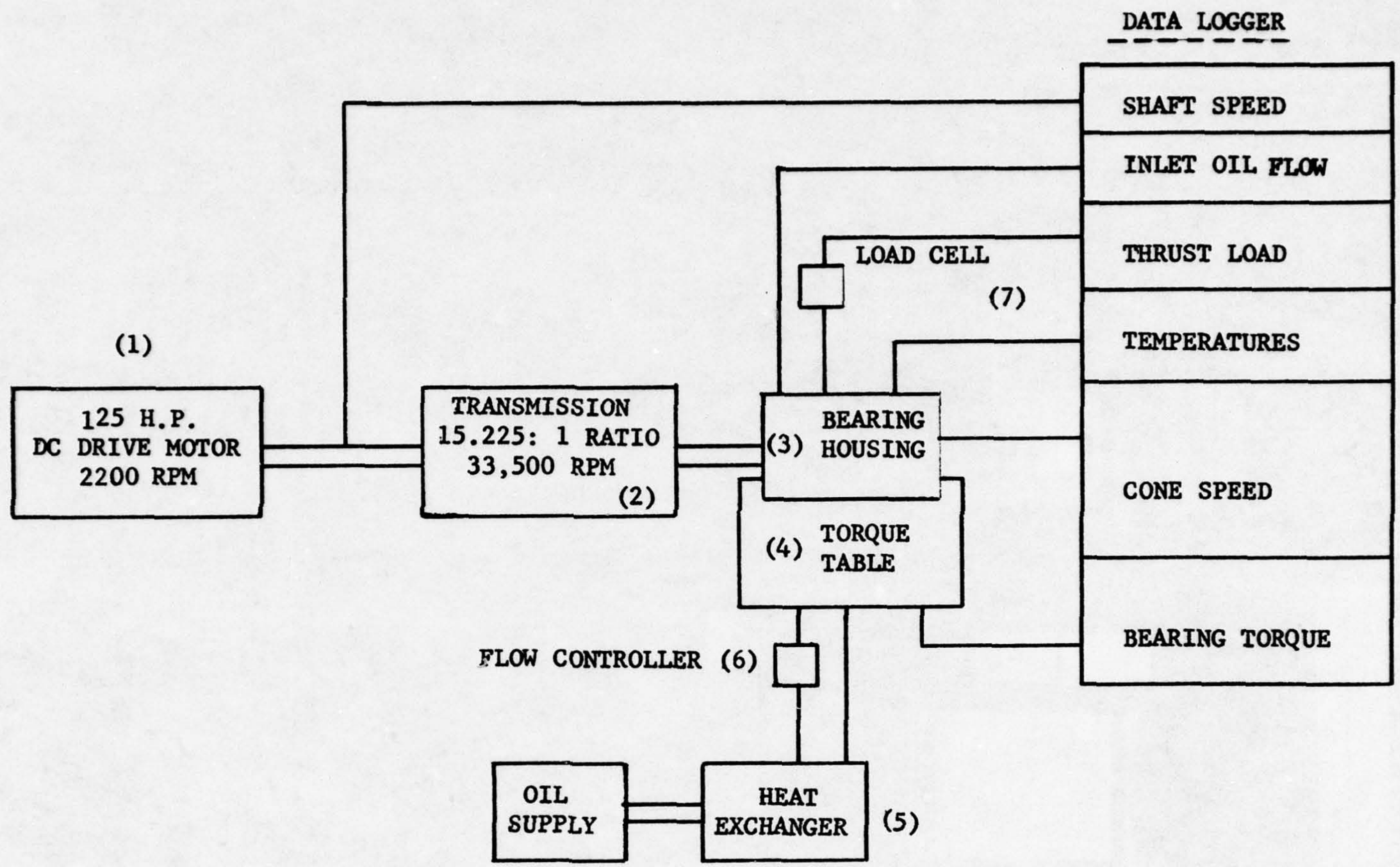


Figure 10. High Speed Test Machine Block Diagram

Thermocouple temperature readings are also recorded on the data logger. The oil inlet thermocouple is located at a point where the stainless steel tubing enters the test housing. Another thermocouple is located in a reservoir used to catch the oil as it leaves the bearing. The bearing cup temperatures were obtained by cementing thermocouples to the cup housing inside diameter. The ambient temperature thermocouple was located approximately four feet from and at the same level as the test housing.

The bearing shaft speed is measured by a magnetic proximity pick-up in conjunction with a 60-tooth gear mounted on the motor output shaft. The resultant signals are relayed to a digital counter. The counter provides a continual visual display of shaft speed and provides a signal to the data logger for printing.

The thrust load is applied to the bearings by means of a 10 in. (254 mm) bore air cylinder. The thrust load is recorded by means of a 10,000 lbf. (44 500 N) capacity load cell (7) monitored by the data logger.

As mentioned above all test data parameters are recorded on the Summa II data logger manufactured by the John Fluke Mfg. Co., Inc. This data logger accepts D.C. volt inputs, thermocouple inputs and digital inputs from other instrumentation. This data logger is equipped with twenty channels and seven alarms. Any alarm can be assigned to any or all twenty channels. In the continuous scan mode all twenty channels are scanned every seven seconds. If any of the alarm limits are exceeded during the scan, the drive motor will immediately shut down.

3.1 Test Lubricant

The lubricating oil used throughout Tasks II and III was Royal Lubricant Company's Mil-L-7808G, supplied by AFAPL/SFL. As the bearing tests were being conducted, oil samples were taken frequently to check lubricant properties. A close watch was given to the lubricant neutralization number (acid number). An acid number of 1.0 was used as the criterion to discard the oil in test and replace with a new supply.

Early in the testing in Task II, the longest time a test oil was used was 182 hours with a final acid number of 2.86. Later in the program as the oil samples were checked at 24 hour intervals, the longest a test oil ran was 72 hours.

The lubricant properties of the oil received from AFAPL/SFL are as follows:

TABLE 2

LUBRICANT PROPERTIES*

Lubricant	Viscosity (cSt) @ 40°C	Viscosity (cSt) @ 100°C	Viscosity Index	pH	Acid No.	Color	Dirt Count
Royal Lubricant Company Mil-L-7808G	12.74	3.48	160	7.05	0.3496	<5.0	0.8 mg/100 mL

* measured values

SECTION IV

CAGE DEVELOPMENT

The tests presented herein represent the short duration developmental tests necessary to evaluate various designs and to verify previous analytical studies.

4.1 Procedure

Each bearing component was visually inspected for surface defects before testing. As the bearings were being manufactured, they underwent close inspection procedures according to The Timken Company's "critical parts" manufacturing plan. The more critical geometry measurements that may influence bearing performance were rechecked before test and recorded. Some of these measurements are the cone rib and race angles, roller size and spherical end radius, surface finish of all contacting surfaces, assembled bearing overall width and the cage shake. Note: Cage shake is the measurement of the radial movement of the cage after it is "closed-in" on the cone. This radial movement is measured in three places to check for concentricity. Throughout the testing, the cages were inspected periodically for any increase in cage shake or expansion in cage O.D. measurements.

Two bearings were tested at a time, one loaded against the other, in the High Speed Bearing Test Machine. Each pair of bearings was allowed to run until steady state conditions were reached at various speeds from 0.50×10^6 through 3.5×10^6 DN. The applied thrust load was 3000 lbf. (13 300 N).

The oil flow to each bearing was 20 pt./min. total, with 10 pt./min. (4.7 L/min.) to the small end of the bearing and 10 pt./min. (4.7 L/min.) to the cone rib.

4.2 Results

A complete listing of all test results and representative performance parameters are shown in Appendix A. A summary of these tests are listed on Table 3. The following is a detailed discussion of these results.

Test No. 1 was started with two new cones and cups and an AISI 4340 steel L-type cage (XC1933AB), phosphate coated. This test ran approximately one hour at 2.5×10^6 DN before bearing damage occurred. After test inspection revealed peeling* of the cone race in the drive end position.

Test No. 2 was run to verify correct operation of the test machine. It was thought that vibration could have caused the peeling in the first test. This test was started with two cones and cups that had been previously tested and a standard AISI 1010 steel L-type cage (L521906), silver plated. Test terminated after five hours at 3×10^6 DN with bearings in excellent condition.

* Peeling or microspalling is a very shallow fatigue spall of the surface that occurs under low EHD film thickness.

TABLE 3

SUMMARY OF CAGE DEVELOPMENT TESTS

Test No.	Cage Design Type	Cage Design Material*	Hours At Maximum Attained Speed	Post Test Condition
1	L	4340/PH	0.8 @ 2.5×10^6 DN	Peeling Drive End Cone OK - Opposite Drive End
2	L	1010/AG	5.0 @ 3.00×10^6 DN	OK
3	L	4340/PH	Damage @ 2.25×10^6 DN	Rib Damage Both Ends
4	L	4340/AG	24 @ 3.50×10^6 DN	OK
5	L	4340/AG	20.2 @ 3.5×10^6 DN	Rib Damage Drive End Cage Damage Opposite Drive End
6	L	4340/AG	16 @ 3.5×10^6 DN	Cage Damage Drive End OK - Opposite Drive End
7	S	1010/AG	0.1 @ 3.5×10^6 DN	OK - Drive End Cage Damage Opposite Drive End
8	S	4340/AG	Damage @ 2.25×10^6 DN	Cage Damage Drive End OK - Opposite Drive End
9	L	Aluminum/AG	0.1 @ 3.5×10^6 DN	Cage Damage Both Ends
10	S	4340/AG	26 @ 3.5×10^6 DN	OK
0	L	4340/FN	Ferritic-Nitrocarburized Cages Cracked At Closing in Operation	
11	Z	4340/AG	0.42 @ 3.5×10^6 DN	Rib Damage - Drive End OK - Opposite Drive End
12	Z	4340/AG	Damage @ 3.5×10^6 DN	Rib Damage - Drive End OK - Opposite Drive End
13	S/DE Z/ODE	4340/AG 4340/AG	Damage @ 2.5×10^6 DN	Rib Damage - Drive End OK - Opposite Drive End
14	S/DE Z/ODE	4340/AG 4340/AG	1.5 @ 3.5×10^6 DN	Rib Damage - Drive End OK - Opposite Drive End
15	Z	4340/AG	Damage @ 3.5×10^6 DN	Rib Damage - Drive End OK - Opposite Drive End
16	Z	4340/AG	32 @ 3.5×10^6 DN	OK

Table 3 (Continued)

Test No.	Cage Design Type	Material*	Hours At Maximum Attained Speed	Post Test Condition
17	Z	4340/AG	0.1 @ 3.5 x 10^6 DN	OK - Drive End Rib Damage - Opposite Drive End
18	Z	4340/AG	23 @ 3.5 x 10^6 DN	OK
19	Z	4340/AG	81 @ 3.5 x 10^6 DN	OK - Drive End Rib Damage - Opposite Drive End
20	Z	4340/AG	Damage @ 3.0 x 10^6 DN	Rib Damage - Drive End OK - Opposite Drive End

* 4340 - AISI 4340 Steel
1010 - AISI 1010 Steel
Aluminum - Type 5052-H32
PH - Phosphate Coated
AG - Silver Plated

Test No. 3 using two XC1933AB cages, silver plated attained a maximum speed of 2.25×10^6 DN before bearing damage occurred in the form of rib/roller end scuffing.

Test No. 4 was run with two previously tested cones and cups and an XC1933AB silver plated cage. This test ran for a total of 58.6 hours, 24.2 hours at the top speed of 3.5×10^6 DN. Both bearings were in excellent condition after test.

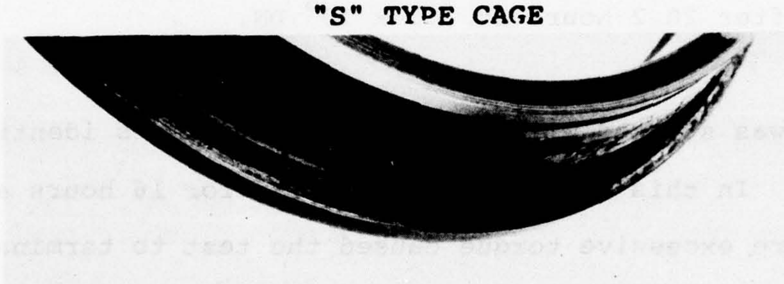
Test No. 5 was conducted with two new cones and cups and XC1933AB silver plated cages. In this test the opposite drive end cage fractured after 20.2 hours at 3.5×10^6 DN.

Test No. 6 was started with new bearing components identical to Test No. 5. In this test the bearings ran for 16 hours at 3.5×10^6 DN before excessive torque caused the test to terminate. After test inspection showed that the drive end cage shake increased 0.099 in. (2.51 mm).

Test No. 7 was run with two new cones and cups and XC1933AC cages, silver plated. In this test the bearings ran for 0.1 hours at 3.5×10^6 DN before the opposite drive end cage fractured. Figure 11 is a photograph of the fracture damaged components.

At this point it was decided to discontinue testing the AISI 1010 steel S-type cages (XC1933AC). The tensile strength of this steel was not adequate. Since AISI 1020 steel is not a significant improvement in strength, it was decided to start testing the AISI 4340 steel S-type cages (XC1933AE).

"S" TYPE CAGE



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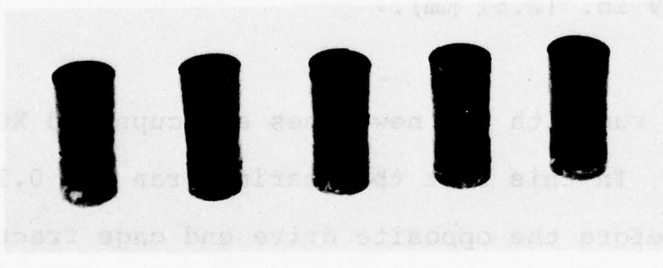


ROLLERS

Figure 11. Damage Bearing Components From Run No. 7

Test No. 8 was run with two new cones and cups and XC1933AE cages, silver plated. This test ran at speeds up to 2.25 x 10^6 DN before excessive torque caused the test to terminate. After test inspection showed that two cage pockets became distorted in the drive end position.

Test No. 9 was conducted with a new bearing in the drive end position and the same bearing in the previous test in the opposite drive end position. Both bearings were fitted with L-type design aluminum cages, aluminum alloy 5052-H32 (XC1933AG). Both cages fractured after running three minutes at 3.5 x 10^6 DN.

Test No. 10 was run with two previously tested cones and cups and two new XC1933AE cages. This test ran for 26 hours at 3.5 x 10^6 DN, both bearings being in excellent condition after test.

Test No. 0 was never assembled in the test machine. The cages used on the bearings were XC1933AB that were ferritic-nitrocarburized by Nemo Heat Treatments Limited, England. This is a surface treatment which forms an epsilon iron carbonitride layer which has resistance to scuffing, seizure and surface fatigue. Both cages cracked when they were closed in before testing.

Test No. 11 was the first test for the AISI 4340 Z-type cages, XC1933AF, silver plated. This test also marked the start of testing with a new lot of cones and cups manufactured for this program. As a result of the cone manifold problem and a new shaft being 0.003 in. (0.08 mm) out-of-round, Test Nos. 11 through 15 were not successful. The out-of-roundness and improper manifold design only occurred at the drive end.

Both XC1933AE and XC1933AF cages were tested in runs 11 through 15. Post test bearing components and an XC1933AF cage are shown on Figure 12.

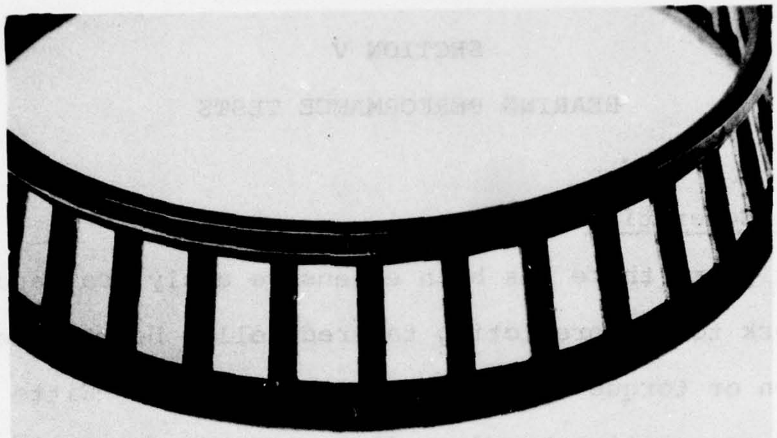
The bearings and cages from Test No. 16 were satisfactory after running 32 hours at 3.5×10^6 DN. The cages in Test Nos. 16 through 20 were the XC1933AF cages.

Test No. 17 resulted in rib/roller end scuffing damage after four minutes at 3.5×10^6 DN. After test inspection revealed that the cage I.D. at the large end rubbed on the cone rib O.D.

Test No. 18 ran satisfactorily for 28 hours at 3.5×10^6 DN.

Test No. 19 was allowed to run for an extended duration to evaluate cone manifold revisions. This test ran for 81 hours at 3.5×10^6 DN before rib/roller end scuffing occurred. This damage was caused by lubricant sludge filling the oil manifold in the I.D. of the cone causing an uneven distribution of oil. At the termination of this test only the damaged bearing (opposite drive end position) was removed and replaced with another bearing for Test No. 20.

Test No. 20 was terminated prematurely at 3.0×10^6 DN due to sludge deposits in the manifold of the drive end bearing. Rib/roller end scuffing resulted. It is assumed that if this debris would have been cleaned out at the conclusion of Test No. 19, this bearing would have run longer.



"Z" TYPE CAGE

CONE

ROLLERS

Figure 12. Damage Bearing Components From Run No. 11

SECTION V

BEARING PERFORMANCE TESTS

5.1 Heat Generation

In recent years there has been extensive analytical and experimental work toward predicting tapered roller bearing heat generation or torque and operating temperature. Witte (ref. 3) developed an equation based on dimensional analyses of variables involved in the elastohydrodynamic contact. His experimental conditions for determining equation exponents and constants were selected to minimize the effects of bulk lubricant and the contribution of the roller end cone rib contact. Test bearing speeds were less the 0.5 million DN. Experimental and analytical work increasing the speed range to 1.8 million DN was recently published by Parker and Signer (ref. 4).

The work presented herein is an extension of these efforts by increasing the speed range. Bearing torque and heat generation were experimentally determined at speeds to 3.5 million DN. The parameters varied in addition to speed included thrust load, inlet lubricant temperature (viscosity), lubricant distribution and cage design. The test conditions are shown on Table 4.

The initial plan had been to equate heat flow into and out of the test housing at thermal equilibrium. This would provide assurance that the instrumentation was accurately monitoring the bearing performance parameters. In the previous program (ref. 1) it had been established that extraneous loading and high ambient temperatures on the torque table had produced significant error.

TABLE 4

HEAT GENERATION TEST CONDITIONS

Cage Design	Oil Flow (Pt./Min.) Races / Cone Rib	Inlet Oil Temperature (^oF)	Speed DN x 10^{-6}	Thrust Load (Lbf.)
XC1933AF (37 Rollers)	10 / 10	210	.25	1000
		210	.25	3000
XC1933AF (37 Rollers)	8 / 12	210	.25	6000
		210	1.00	1000
XC1933AF (37 Rollers)	12 / 8	210	1.00	3000
		210	1.00	6000
XC1933AE (39 Rollers)	10 / 10	210	2.25	1000
		210	2.25	3000
		210	2.25	6000
		210	3.5	3000
		210	3.5	*4500
		300	.25	1000
		300	.25	3000
		300	.25	6000
		300	1.00	1000
		300	1.00	3000
		300	1.00	6000
		300	2.25	1000
		300	2.25	3000
		300	2.25	6000
		300	3.5	3000
		300	3.5	4500

* Initial test run under 6000 lbf. thrust load. Subsequent tests run at 4500 lbf. thrust due to two incidences of rib damage; this damage occurred at each position.

The heat flow balance consisted of power to the bearings as measured by torque and speed and heat flow out via the oil and housing losses. A preliminary test was conducted to establish housing heat transfer rates as a function of oil/bearing temperatures. The approach used was to vary the inlet oil temperature and adjust bearing load and speed so the net change in oil temperature through the housing was zero. Under these conditions bearing power requirements equaled the housing heat losses. This balance ($\Delta T = 0$) was attained at several temperature levels; however, instrumentation accuracy produced considerable data scatter and no significant functional housing heat loss rates could be established. The tests did show that for this test rig,* housing heat losses represent a small percentage of heat generated.

The test procedure then was as follows:

1) Prior to start, torque table, thermocouples and flow meters were calibrated.

2) The test parameters were applied and the test run until temperatures stabilized.

3) The torque table was recalibrated at operating temperature.

4) The test was run from 30 to 90 minutes recording data at 15 minute increments.

All test data is shown in Appendix A.

* Test housing had been insulated with 1/2 in. fiber insulation.

Discussion of Results

Least-square fitted power functions of torque for the two test bearings as a function of load and speed are shown on Figures 13 through 16. The upper curves represent data recorded with oil inlet temperatures of nominally 210°F (99°C) and the lower set at 300°F (149°C). This represents a range of 2:1 in kinematic viscosity (3.16 cSt @ 210°F and 1.57 cSt @ 300°F). The first three sets of graphs represent the effects of varied oil flow distributions. The test bearings had the race guided Z-type cages. The tests were conducted with 8, 10 and 12 pt./min. (3.8, 4.7 and 5.7 L/min.) to the cone rib and roller small ends while maintaining constant total flows of 20 pt./min. (9.5 L/min.) per bearing. The narrow range of flows was dictated by machine pumping capacity and pipe size. The final curves shown on Figure 16 represent the tests conducted with a cage design variation. Uniform oil flow was pumped to a roller guided, S-type cage.

To evaluate the data presented it would be useful to review the Witte equations for bearing torque.

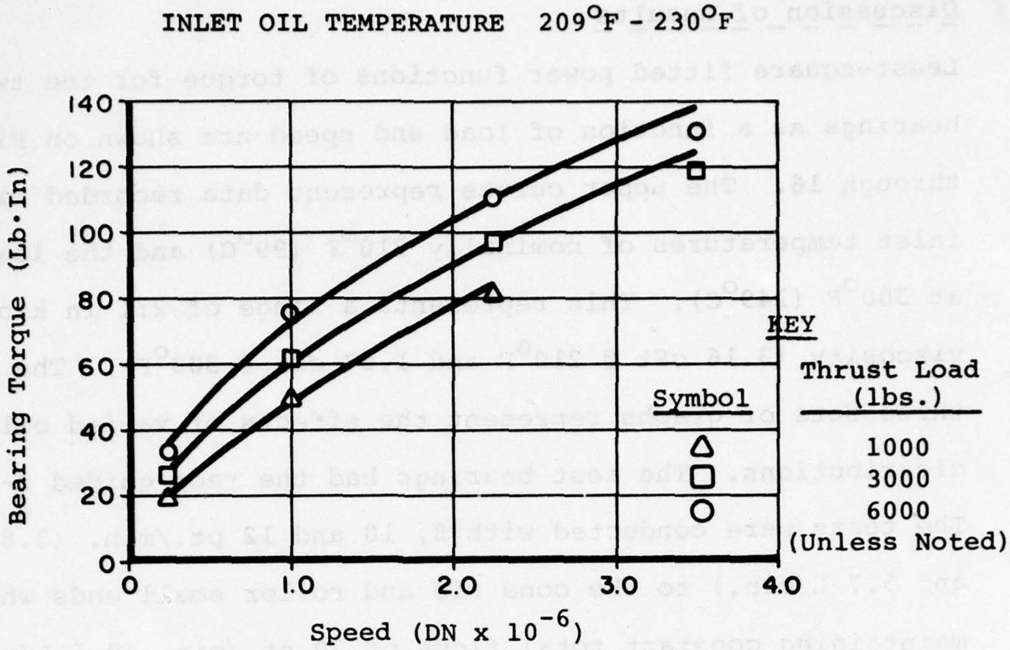
$$M = 1.1 \times 10^{-4} G \, (S\mu)^{1/2} \, (F_a)^{1/3}$$

where the bearing geometry factor is

$$G = D_p^{3/2} \, D^{1/6} \, (n\ell)^{2/3} \, (\mathrm{Sin}\alpha)^{-1/3}$$

and D = mean roller diameter, in.
D_p = pitch diameter, in.
n = number of rollers
ℓ = roller-race contact length, in.
α = 1/2 included cup angle
S = cone speed, rev./min.
μ = lubricant absolute viscosity, cp
F_a = thrust load, lbf.

Using these equations and lubricant viscosity at the outlet, torque estimates were calculated at each test condition.



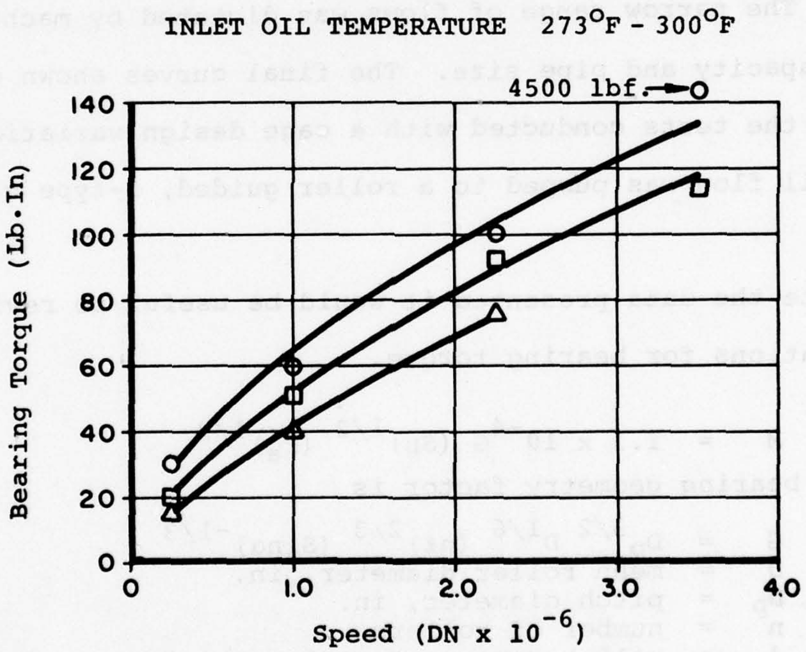
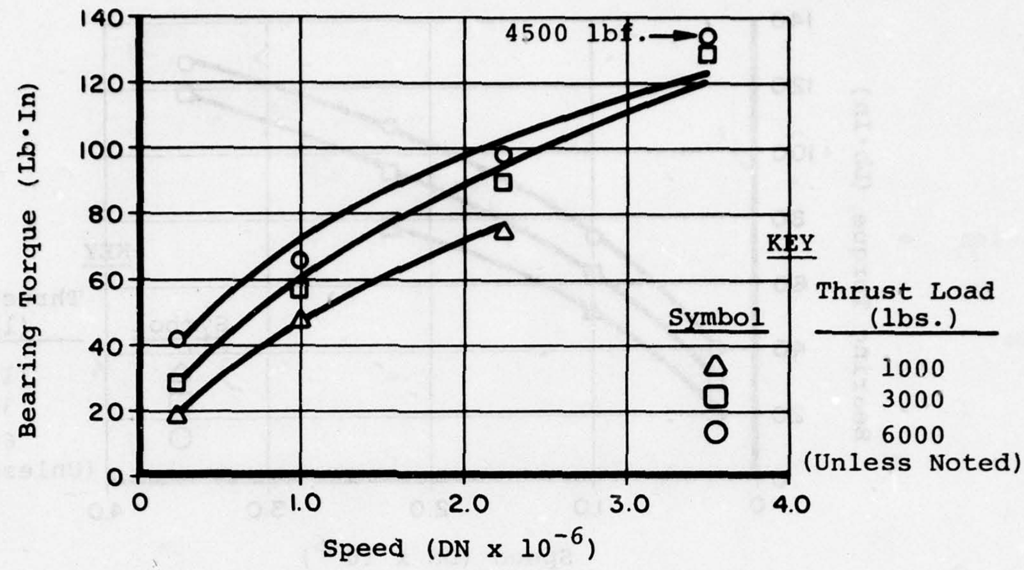


Figure 13. Bearing (2) Torque Versus Speed at Three Loads
Cage - XC1933AF, 37 Rollers
Oil Flow - 10 Pints/Minute Jetted to Small End of Rollers
10 Pints/Minute to Cone Rib

INLET OIL TEMPERATURE 209°F - 245°F



INLET OIL TEMPERATURE 296°F - 300°F

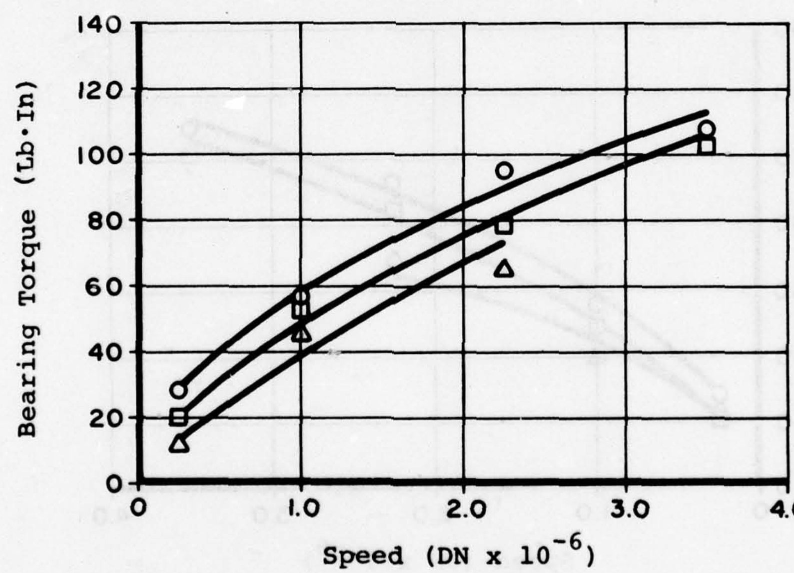
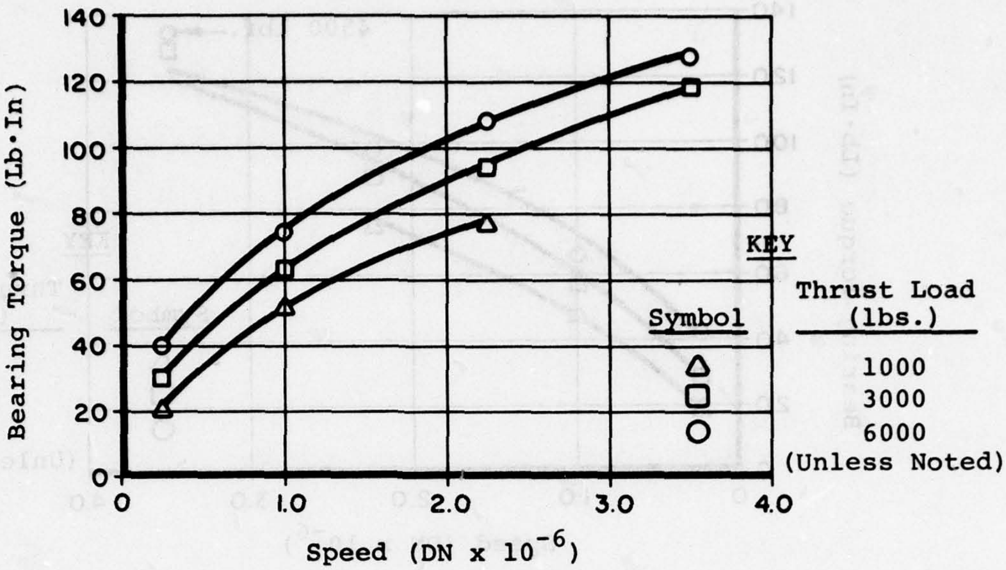


Figure 14. Bearing (2) Torque Versus Speed at Three Loads
Cage - XC1933AF, 37 Rollers
Oil Flow - 8 Pints/Minute Jetted to Small End of Rollers
12 Pints/Minute to Cone Rib

INLET OIL TEMPERATURE 209°F - 243°F



INLET OIL TEMPERATURE 290°F - 303°F

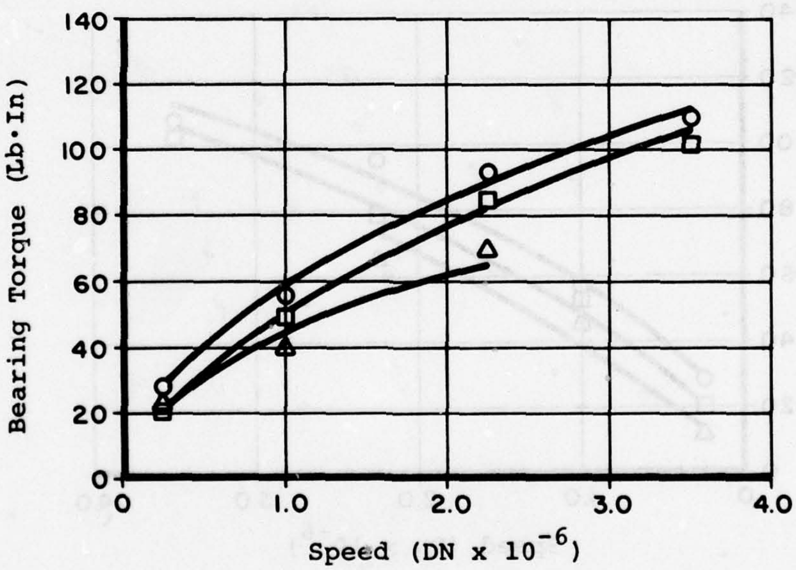


Figure 15. Bearing (2) Torque Versus Speed at Three Loads
Cage - XC1933AF, 37 Rollers
Oil Flow - 12 Pints/Minute Jetted to Small End of Rollers
8 Pints/Minute to Cone Rib

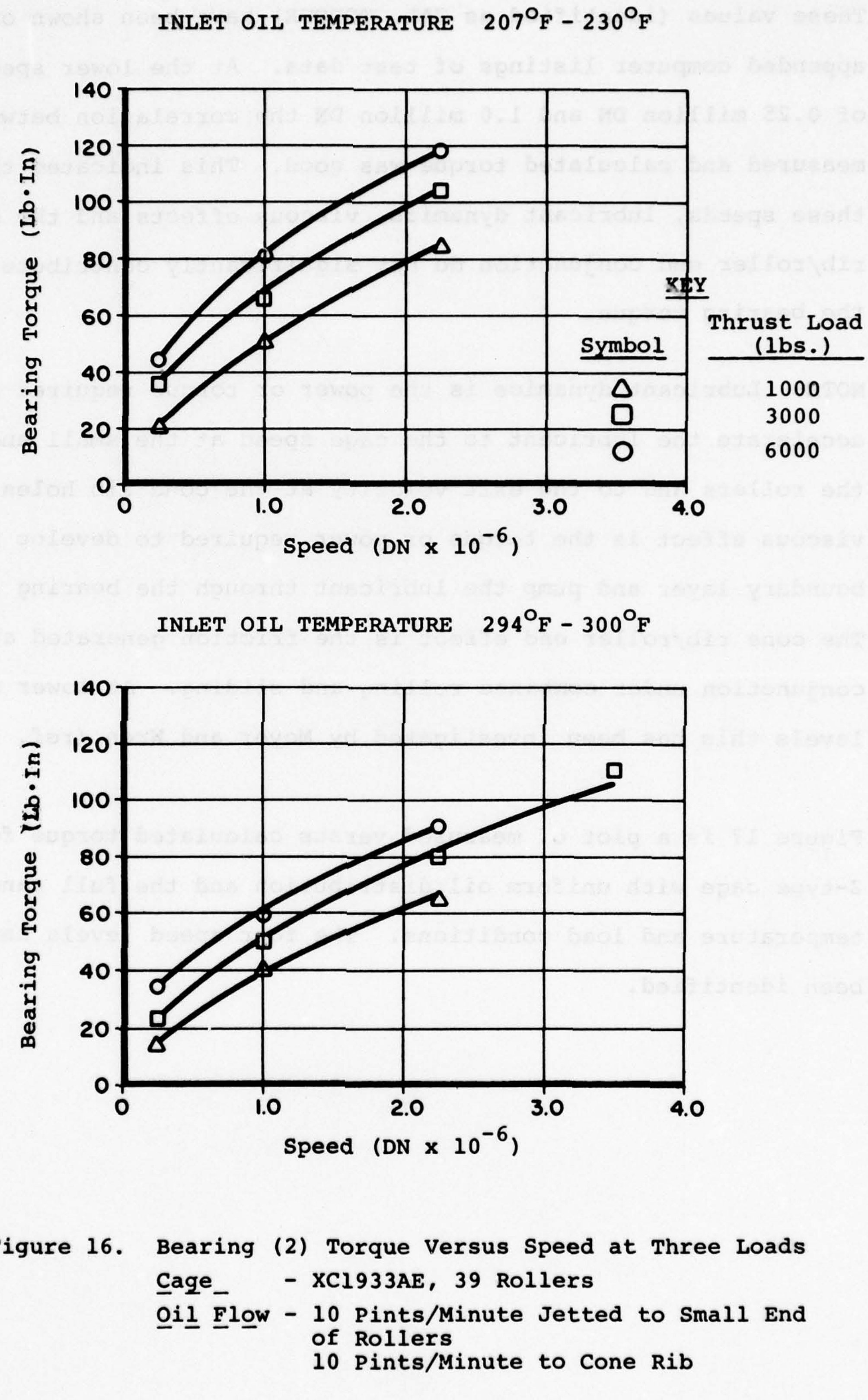


Figure 16. Bearing (2) Torque Versus Speed at Three Loads
Cage - XC1933AE, 39 Rollers
Oil Flow - 10 Pints/Minute Jetted to Small End of Rollers
10 Pints/Minute to Cone Rib

These values (identified as CAL. TORQUE) have been shown on the appended computer listings of test data. At the lower speeds of 0.25 million DN and 1.0 million DN the correlation between measured and calculated torque was good. This indicated that at these speeds, lubricant dynamics, viscous effects and the cone rib/roller end conjunction do not significantly contribute to the bearing torque.

NOTE: Lubricant dynamics is the power or torque required to accelerate the lubricant to the cage speed at the small end of the rollers and to the exit velocity at the cone rib holes. The viscous effect is the torque or power required to develop a boundary layer and pump the lubricant through the bearing (ref. 5). The cone rib/roller end effect is the friction generated at this conjunction under combined rolling and sliding. At lower speed levels this has been investigated by Moyer and Wren (ref. 6).

Figure 17 is a plot of measured versus calculated torque for the Z-type cage with uniform oil distribution and the full range of temperature and load conditions. The four speed levels have been identified.

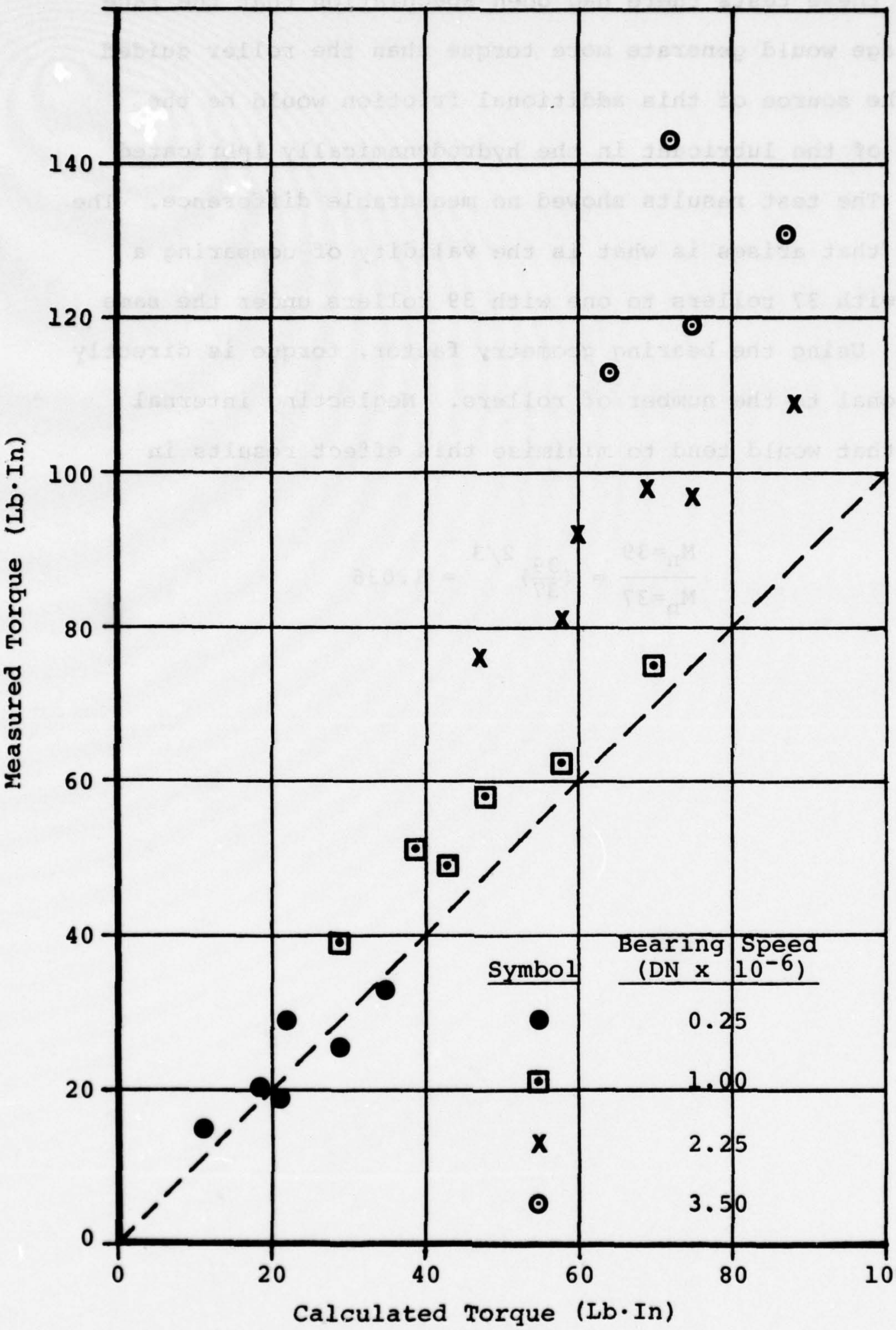


Figure 17. Correlation of Measured and Calculated Torques at Various Speed Levels

Prior to these tests there had been speculation that the race guided cage would generate more torque than the roller guided cage. The source of this additional friction would be the shearing of the lubricant in the hydrodynamically lubricated guides. The test results showed no measurable difference. The question that arises is what is the validity of comparing a bearing with 37 rollers to one with 39 rollers under the same loading. Using the bearing geometry factor, torque is directly proportional to the number of rollers. Neglecting internal loading that would tend to minimize this effect results in

$$\frac{M_{n=39}}{M_{n=37}} = \left(\frac{39}{37}\right)^{2/3} = 1.036$$

5.2 Oil Off Tests

Four bearings that had been tested previously were prepared for test. The first oil off test was run with an XC1933AF cage, and the second test with an XC1933AE cage. In both tests the bearings were operated until temperatures stabilized at 1.5 x 10^6 DN shaft speed, 2000 lbf. (8 900 N) thrust load, 10 pt./min. (4.7 L/min.) oil flow to both the cone rib and small end. The oil inlet temperature was 250°F (121°C).

After the above conditions were met, the lubrication supply pump was turned off. Cup temperatures and bearing torque were continually monitored. A torque limit of 175 in·lb (19.8 N·m) was set to stop the drive motor. The XC1933AF ran for 86 seconds and the XC1933AE for 99 seconds.

Both tests acted very similar in their torque characteristics as seen on Figure 18. The torque of both tests dropped off sharply in the first 10 seconds, leveled off for the next 35 seconds, then increased to what it was at the start of the test. For the next 35 to 40 seconds the torque was erratic before increasing very sharply to shut down.

Figure 19 is a graph showing the bearing cup O.D. temperatures of the drive end and opposite drive end of both tests. In both tests only drive end bearings were damaged. It can be readily seen on Figure 19 that the drive end cup temperatures increased the most.

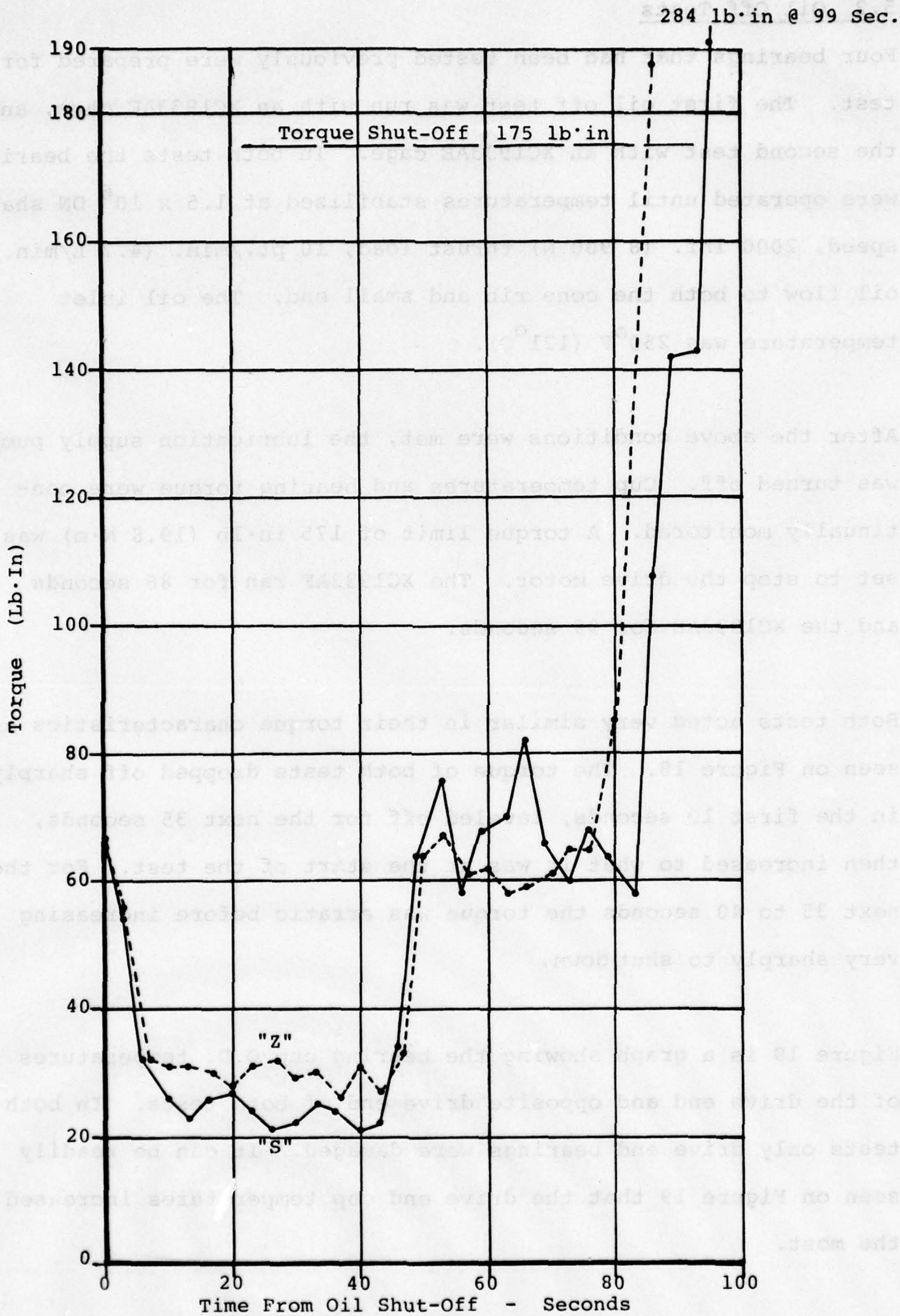


Figure 18. Oil Off Torque Characteristics

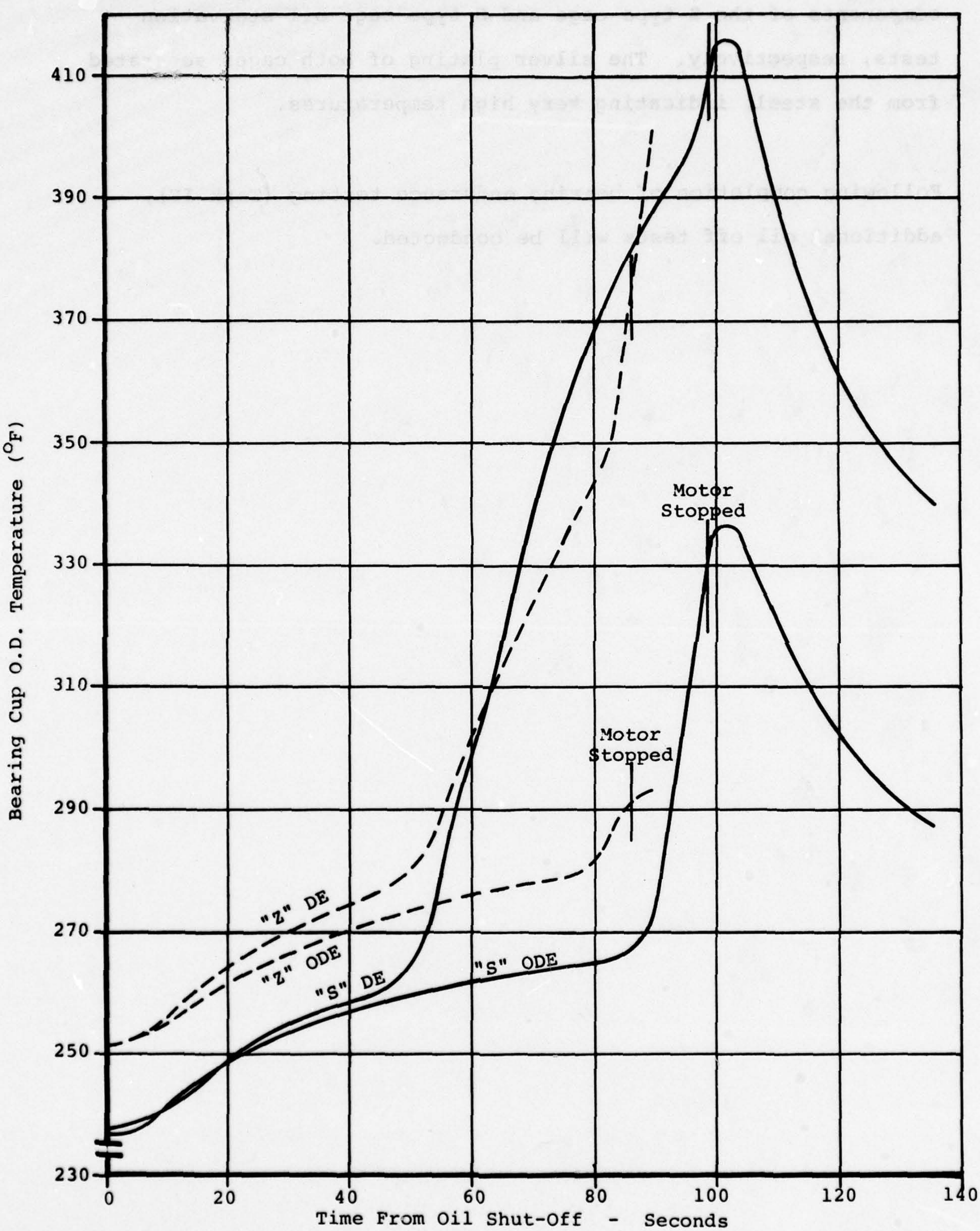
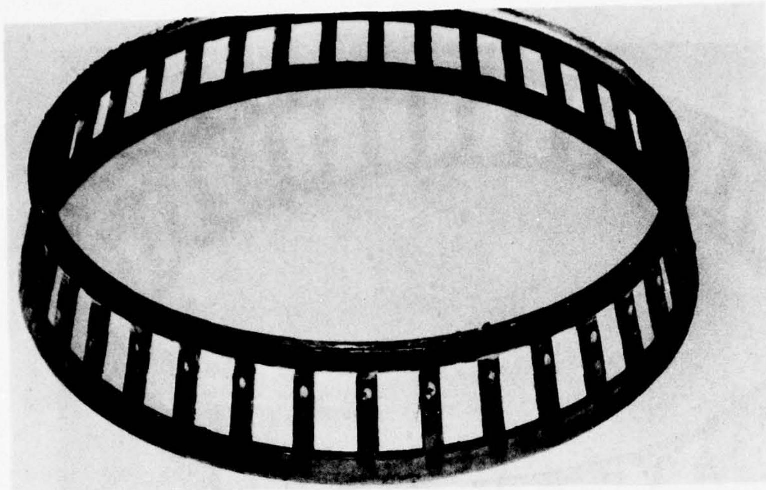


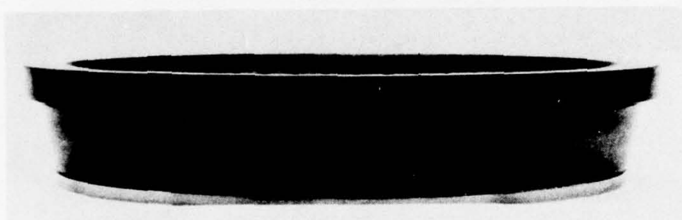
Figure 19. **Oil Off Bearing Temperatures**

Figures 20 and 21 are photographs showing the damaged bearing components of the Z-type cage and S-type cage oil starvation tests, respectively. The silver plating of both cages separated from the steel, indicating very high temperatures.

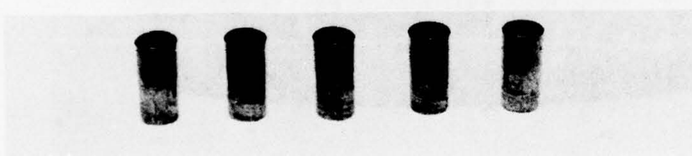
Following completion of bearing endurance testing (Task IV), additional oil off tests will be conducted.



"Z" TYPE CAGE



CONE

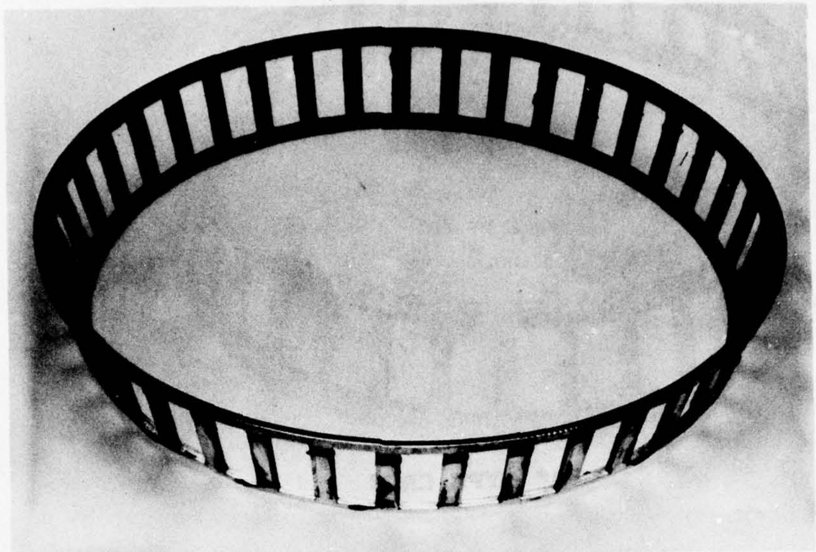


ROLLERS

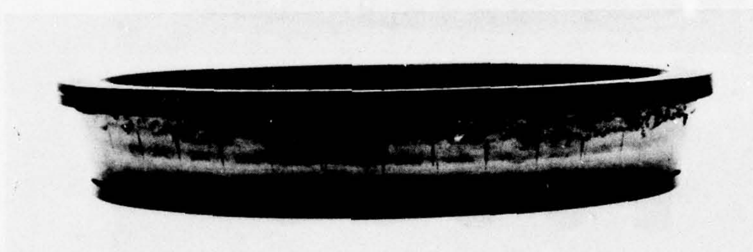
LARGE END

CUP SMALL END

Figure 20. Condition of Bearing Components After Oil Starvation Test - 86 Seconds Without Oil



"S" TYPE CAGE



CONE

ROLLERS

Figure 21. Condition of Bearing Components After Oil Starvation Test - 99 Seconds Without Oil

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Consistent with the findings of the analytical studies the machined, race guided cages proved to be the best design. In the short duration developmental tests, eight cages were tested in ten trial runs. None of these cages fractured although several of the bearings were damaged. The tests with cage related bearing damage were a result of insufficient clearance between the cage inside diameter and cone rib outside diameter. By revising the design to increase this clearance this problem was eliminated. The other instances of bearing damage were caused by improper cone manifold location, since corrected, and thermal degradation of the lubricant.

The roller guided cages manufactured with higher strength steels or aluminum could not reliably operate at 3.5 million DN. These designs did show improvements over the conventional cages and could possibly be used in lower speed applications.

An overview of the test results indicated a significant greater incidence of damage occurring at the drive end position. This machine position influence can be attributed to higher vibration levels due to the adjacent gear drive, coupling and bearing mounting design. Test rig revisions have been initiated to minimize this effect.

The bearing performance tests indicated the following:

1) There is no measurable difference in heat generation rates comparing the roller or race guided cage designs.

2) Bearing torque at high speeds are not sensitive to oil flow distribution (flow to roller small end and cone rib). Flow rates were above the threshold needed to lubricate the bearing.

3) The methodology used to predict bearing torque for conventional speed condition is adequate up to 1.0 million DN. Beyond this speed, lubricant and cone rib/roller end effects must be considered.

4) At the 1.5 million DN speed and 2000 lbf. (8 900 N) thrust load, the XC1933 bearings can sustain rotation for greater than one minute without any oil being supplied. This is a conservative estimate since in the test a torque increase of approximately 100 percent was used as a limit.

Recommendations

The primary effort now should be concentrated on evaluating the XC1933 series high speed tapered roller bearing equipped with the machined, race guided, Z-type cage. An alternate lubricant should be used in the long term endurance tests. This lubricant must be able to maintain its properties at continuous operating temperatures of 400°F (204°C).

APPENDIX A

CAGE DEVELOPMENT TEST DATA

RUN NØ 1

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 47	73 - 79
CUP NØ.	73 - 19	73 - 34
CAGE DESIGN	AB / PH	AB / PH
PØST TEST CØNDITIØN	PEELING	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	1.2	3000	60.0	10.0	10.0	145	153	154	145	154	156
.75	.5	3000	71.0	10.0	10.0	165	178	180	165	181	181
.50	1.0	3000	58.0	10.0	10.0	140	147	147	140	149	151
.75	1.0	3000	56.0	10.0	10.0	189	199	199	189	201	201
1.00	1.0	3000	62.0	10.0	10.0	199	217	221	199	221	57
1.50	1.0	3000	73.0	10.0	10.0	226	257	261	226	262	257
2.00	1.0	3000	78.0	10.0	10.0	270	313	311	270	316	304
2.25	1.0	3000	77.0	10.0	10.0	307	354	352	307	358	342
2.50	.3	3000	92.0	10.0	10.0	304	374	360	304	365	374
2.50	.5	3000	96.0	10.0	10.0	304	378	358	304	365	387

RUN NØ 2

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 40	73 - 56
CUP NØ.	73 - 10	73 - 17
CAGE DESIGN	SD / AG	SD / AG
PØST TEST CØNDITIØN	ØK	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.7	3000	56.0	10.0	10.0	217	214	211	217	218	204
.50	.5	3000	46.0	10.0	10.0	188	191	191	188	193	187
.50	.7	3000	69.0	10.0	10.0	153	158	159	153	161	155
.50	.2	3000	52.0	10.0	10.0	156	162	163	156	164	158
.75	.7	3000	58.0	10.0	10.0	202	223	225	203	228	226
.75	.5	3000	53.0	10.0	10.0	198	208	210	198	212	208
.75	.5	3000	56.0	10.0	10.0	205	214	214	205	217	210
.75	.5	3000	56.0	10.0	10.0	187	198	199	187	201	196
1.00	1.0	3000	65.0	10.0	10.0	203	223	225	203	228	226
1.00	.5	3000	60.0	10.0	10.0	217	232	234	217	239	234
1.00	.5	3000	60.0	10.0	10.0	244	257	257	244	262	255
1.00	.5	3000	57.0	10.0	10.0	212	228	230	212	234	230
1.50	.5	3000	66.0	10.0	10.0	244	273	271	244	280	273
1.50	.5	3000	65.0	10.0	10.0	298	320	316	298	325	318
1.50	.5	3000	67.0	10.0	10.0	268	293	291	268	298	291
2.00	1.0	3000	78.0	10.0	10.0	297	336	327	297	343	334
2.00	.5	3000	92.0	10.0	10.0	311	349	340	311	354	345
2.00	.5	3000	74.0	10.0	10.0	307	347	338	307	351	343
2.25	1.0	3000	83.0	10.0	10.0	320	367	352	320	372	365

2.25	.5	3000	89.0	10.0	10.0	306	354	342	306	360	351
2.50	.5	3000	90.0	10.0	10.0	300	360	343	300	365	358
2.50	.5	3000	93.0	10.0	10.0	302	361	345	302	369	360
2.75	.5	3000	96.0	10.0	10.0	295	363	343	295	370	340
2.75	.2	3000	94.0	10.0	10.0	304	372	352	304	379	369
3.00	1.0	3000	102.0	10.0	10.0	311	387	363	311	394	381
3.00	4.0	3000	97.0	10.0	10.0	309	388	365	309	394	383

This test was run to check out the operation of the test machine. At the end of 5 hours at 3.00E6 DN, the standard silver plated cages were removed and replaced with two "L" type 4340 steel phosphate coated cages for Test No. 3.

RUN NØ 3

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 40	73 - 56
CUP NØ.	73 - 10	73 - 17
CAGE DESIGN	AB / PH	AB / PH
PØST TEST CØNDITIØN	RIB DAMAGE	RIB DAMAGE

Rib/Roller end damage occurred at 2.25E6 DN.

R U N N Ø 4

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 21	73 - 22
CUP NØ.	73 - 3	73 - 4
CAGE DESIGN	AB / AG	AB / AG
PØST TEST CØNDITIØN	ØK	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.5	3000	52.0	10.0	10.0	171	176	176	171	180	171
.50	.5	3000	54.0	10.0	10.0	151	158	160	151	160	154
.50	.2	3000	65.0	10.0	10.0	135	136	136	135	142	133
.50	.2	3000	54.0	10.0	10.0	172	172	169	172	176	165
.50	.5	3000	63.0	10.0	10.0	165	165	162	165	169	158
.50	.2	3000	45.0	10.0	10.0	189	187	183	189	190	178
.50	.2	3000	48.0	10.0	10.0	196	192	185	196	196	178
.50	.2	3000	74.0	10.0	10.0	172	171	165	172	174	160
.75	1.0	3000	47.0	10.0	10.0	208	217	219	208	219	217
.75	.2	3000	66.0	10.0	10.0	178	187	187	178	190	183
.75	.2	3000	49.0	10.0	10.0	201	207	208	201	210	201
.75	.2	3000	51.0	10.0	10.0	198	203	199	198	207	196
.75	.2	3000	49.0	10.0	10.0	217	221	219	217	225	216
.75	.2	3000	43.0	10.0	10.0	216	221	217	216	223	212
.75	.2	3000	47.0	10.0	10.0	225	228	225	225	230	219
.75	.2	3000	38.0	10.0	10.0	219	225	223	219	228	219
1.00	.5	3000	50.0	10.0	10.0	237	252	252	237	255	252
1.00	.5	3000	69.0	10.0	10.0	205	221	223	205	225	219
1.00	.5	3000	67.0	10.0	10.0	250	261	261	250	264	257

1.00	.2	3000	52.0	10.0	10.0	235	244	241	235	248	239
1.00	.2	3000	61.0	10.0	10.0	248	255	255	248	261	252
1.00	.2	3000	50.0	10.0	10.0	234	244	244	234	250	243
1.00	.2	3000	52.0	10.0	10.0	255	262	261	255	268	257
1.00	.2	3000	37.0	10.0	10.0	270	275	273	270	280	273
1.50	.7	3000	55.0	10.0	10.0	300	324	322	300	329	324
1.50	.7	3000	72.0	10.0	10.0	280	302	302	280	307	300
1.50	.5	3000	63.0	10.0	10.0	295	318	316	295	322	316
1.50	.2	3000	70.0	10.0	10.0	270	291	289	270	297	289
1.50	.2	3000	65.0	10.0	10.0	280	300	298	280	306	298
1.50	.2	3000	56.0	10.0	10.0	266	289	286	266	293	286
1.50	.2	3000	62.0	10.0	10.0	295	315	311	295	320	311
1.50	.2	3000	54.0	10.0	10.0	280	306	304	280	309	304
1.50	.5	3000	75.0	10.0	10.0	279	297	295	279	302	293
2.00	2.0	3000	65.0	10.0	10.0	304	343	338	304	349	343
2.00	.2	3000	78.0	10.0	10.0	304	342	336	304	347	340
2.00	.5	3000	73.0	10.0	10.0	309	349	342	309	352	347
2.00	.2	3000	76.0	10.0	10.0	302	336	329	302	342	333
2.00	.2	3000	80.0	10.0	10.0	302	340	331	302	343	336
2.00	.2	3000	75.0	10.0	10.0	300	336	329	300	342	333
2.00	.2	3000	78.0	10.0	10.0	302	340	333	302	343	336
2.00	.2	3000	72.0	10.0	10.0	298	334	327	298	338	333
2.00	.2	3000	78.0	10.0	10.0	302	336	329	302	342	333
2.25	.7	3000	88.0	10.0	10.0	298	347	340	298	352	347
2.25	.5	3000	82.0	10.0	10.0	302	351	340	302	354	349
2.25	.5	3000	80.0	10.0	10.0	302	347	338	302	349	345

2.25	.5	3000	86.0	10.0	10.0	306	352	342	306	356	351
2.25	.2	3000	86.0	10.0	10.0	277	329	320	277	331	329
2.25	.5	3000	88.0	10.0	10.0	293	343	334	293	345	343
2.25	.5	3000	73.0	10.0	10.0	298	345	336	298	347	343
2.25	.2	3000	86.0	10.0	10.0	293	342	333	293	345	340
2.50	.2	3000	92.0	10.0	10.0	300	360	347	300	365	358
2.50	.5	3000	86.0	10.0	10.0	300	360	345	300	361	358
2.50	.5	3000	94.0	10.0	10.0	288	349	336	288	351	347
2.50	.5	3000	96.0	10.0	10.0	300	358	345	300	361	356
2.50	.2	3000	95.0	10.0	10.0	259	327	315	259	327	327
2.50	.2	3000	92.0	10.0	10.0	297	356	343	297	358	354
2.50	.2	3000	71.0	10.0	10.0	300	358	345	300	361	354
2.50	.5	3000	91.0	10.0	10.0	304	361	347	304	365	356
2.75	.5	3000	95.0	10.0	10.0	300	369	351	300	374	351
2.75	1.2	3000	88.0	10.0	10.0	300	369	352	300	370	365
2.75	.5	3000	98.0	10.0	10.0	297	365	349	297	367	363
2.75	.5	3000	101.0	10.0	10.0	304	372	356	304	374	369
2.75	.5	3000	98.0	10.0	10.0	279	360	347	279	356	358
2.75	.5	3000	99.0	10.0	10.0	295	363	345	295	365	361
2.75	.5	3000	76.0	10.0	10.0	302	370	354	302	372	367
2.75	.5	3000	101.0	10.0	10.0	297	365	349	297	367	361
3.00	1.0	3000	104.0	10.0	10.0	304	381	360	304	385	378
3.00	.2	3000	92.0	10.0	10.0	304	381	361	304	383	376
3.00	.5	3000	101.0	10.0	10.0	297	378	358	297	378	372
3.00	.5	3000	107.0	10.0	10.0	304	383	361	304	383	376
3.00	.5	3000	105.0	10.0	10.0	268	354	333	268	354	349

3.00	.5	3000	102.0	10.0	10.0	295	378	356	295	378	370
3.00	.5	3000	80.0	10.0	10.0	304	381	360	304	383	376
3.00	.5	3000	107.0	10.0	10.0	300	381	360	300	381	374
3.25	1.0	3000	106.0	10.0	10.0	295	385	361	295	388	381
3.25	.5	3000	93.0	10.0	10.0	300	390	367	300	392	385
3.25	.5	3000	107.0	10.0	10.0	298	388	365	298	390	383
3.25	.5	3000	111.0	10.0	10.0	300	390	365	300	392	383
3.25	.5	3000	108.0	10.0	10.0	284	383	360	284	381	378
3.25	.5	3000	109.0	10.0	10.0	298	390	365	298	390	385
3.25	.5	3000	89.0	10.0	10.0	286	378	354	286	379	374
3.25	.5	3000	114.0	10.0	10.0	300	390	365	300	394	385
3.50	2.0	3000	107.0	10.0	10.0	302	403	376	302	406	401
3.50	2.2	3000	101.0	10.0	10.0	306	403	376	306	405	397
3.50	1.5	3000	116.0	10.0	10.0	298	399	372	298	399	394
3.50	4.0	3000	118.0	10.0	10.0	302	403	372	302	403	397
3.50	4.0	3000	114.0	10.0	10.0	284	388	358	284	390	383
3.50	4.0	3000	116.0	10.0	10.0	302	403	374	302	405	396
3.50	4.0	3000	95.0	10.0	10.0	304	406	376	304	405	401
3.50	2.5	3000	117.0	10.0	10.0	302	405	376	302	406	399

24.2 Hours at 3.5E6 DN
34.4 Hours at all lower speeds

58.6 Total

RUN NØ 5

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 34	73 - 41
CUP NØ.	73 - 3	73 - 4
CAGE DESIGN	AB / AG	AB / AG
PØST TEST CØNDITIØN	RIB DAMAGE	CAGE DAMAGE

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	ØUT	CUP	ØDE IN	ØUT	CUP
.50	.5	3000	31.0	10.0	10.0	210	207	201	210	210	199
.75	.2	3000	37.0	10.0	10.0	226	232	230	226	234	228
1.00	.2	3000	49.0	10.0	10.0	237	250	250	237	253	250
1.50	.2	3000	58.0	10.0	10.0	255	280	280	255	286	282
2.00	.2	3000	68.0	10.0	10.0	293	331	324	293	336	329
2.25	.5	3000	73.0	10.0	10.0	295	345	334	295	349	343
2.50	.5	3000	75.0	10.0	10.0	295	356	343	295	358	356
2.75	.5	3000	81.0	10.0	10.0	293	365	315	293	369	363
3.00	.2	3000	81.0	10.0	10.0	297	378	358	297	381	376
3.25	.2	3000	91.0	10.0	10.0	293	387	361	293	388	383
3.50	4.0	3000	108.0	10.0	10.0	280	387	360	280	388	385
3.50	4.0	3000	108.0	10.0	10.0	295	397	370	295	401	396
3.50	4.0	3000	105.0	10.0	10.0	293	397	370	293	399	397
3.50	4.0	3000	102.0	10.0	10.0	293	396	381	293	399	394
3.50	4.0	3000	112.0	10.0	10.0	291	396	381	291	399	392

Opposite drive end cage broke after 20.2 hours at 3.5E6 DN.
Speeds <3.5E6 represent one day's run only.

R U N N Ø 6

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 58	73 - 83
CUP NØ.	73 - 3	73 - 4
CAGE DESIGN	AB / AG	AB / AG
PØST TEST CØNDITIØN	CAGE DAMAGE	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	ØIL FLØW (PT/MIN) LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.5	3000	47.0	10.0	10.0	208	203	192	208	205	187
.75	.2	3000	50.0	10.0	10.0	271	270	262	271	273	257
1.00	.2	3000	65.0	10.0	10.0	248	262	261	248	264	259
1.50	.2	3000	87.0	10.0	10.0	261	286	284	261	289	282
2.00	.2	3000	87.0	10.0	10.0	282	324	318	282	325	316
2.25	.5	3000	106.0	10.0	10.0	237	298	295	237	297	295
2.50	.2	3000	103.0	10.0	10.0	286	345	336	286	347	336
2.75	.5	3000	117.0	10.0	10.0	207	297	291	207	295	291
3.00	.2	3000	123.0	10.0	10.0	217	316	307	217	313	306
3.25	2.5	3000	119.0	10.0	10.0	311	399	381	311	399	381
3.50	4.0	3000	125.0	10.0	10.0	234	358	343	234	356	347
3.50	4.0	3000	128.0	10.0	10.0	239	360	347	239	360	351
3.50	4.0	3000	134.0	10.0	10.0	223	349	336	223	347	340
3.50	4.0	3000	131.0	10.0	10.0	225	351	336	225	349	340

Drive end cage shake increased .099" after 16 hours at 3.5E6 DN.

R U N N Ø 7

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 82	73 - 89
CUP NØ.	73 - 20	73 - 29
CAGE DESIGN	AC / AG	AC / AG
PØST TEST CØNDITIØN	ØK	CAGE DAMAGE

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	ØIL FLØW (PT/MIN) LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.5	3000	42.0	10.0	10.0	187	185	181	187	190	178
.75	.2	3000	44.0	10.0	10.0	212	217	216	212	223	214
1.00	.2	3000	53.0	10.0	10.0	235	248	246	235	253	244
1.50	.2	3000	76.0	10.0	10.0	243	271	271	243	277	271
2.00	.2	3000	73.0	10.0	10.0	259	304	302	259	307	300
2.25	.5	3000	87.0	10.0	10.0	259	306	302	259	307	302
2.50	.5	3000	94.0	10.0	10.0	255	324	320	255	325	318
2.75	.5	3000	94.0	10.0	10.0	252	331	327	252	333	325
3.00	.2	3000	97.0	10.0	10.0	262	349	343	262	349	340
3.25	.5	3000	106.0	10.0	10.0	259	360	352	259	358	351
3.50	.1	3000	113.0	10.0	10.0	279	387	376	279	388	374

Opposite drive end cage broke after .1 hours at 3.5E6 DN.

R U N N Ø 8

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 45	73 - 80
CUP NØ.	73 - 32	73 - 40
CAGE DESIGN	AE / AG	AE / AG
PØST TEST CØNDITIØN	CAGE DAMAGE	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	ØUT	CUP	ØDE IN	ØUT	CUP
.50	.3	3000	46.0	10.0	10.0	165	162	154	165	167	153
.75	.2	3000	44.0	10.0	10.0	234	237	234	234	237	230
1.00	.2	3000	69.0	10.0	10.0	208	225	226	208	228	225
1.50	.2	3000	86.0	10.0	10.0	219	250	250	219	253	250
2.00	.2	3000	84.0	10.0	10.0	232	279	277	232	284	279

Two pockets of the drive end cage distorted at 2.25E6 DN.

RUN NØ 9

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 27	73 - 80
CUP NØ.	73 - 22	73 - 32
CAGE DESIGN	AG / AG	AG / AG
PØST TEST CØNDITIØN	CAGE DAMAGE	CAGE DAMAGE

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	ØIL FLØW (PT/MIN) LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.7	3000	47.0	10.0	10.0	228	226	221	228	228	219
.75	.2	3000	54.0	10.0	10.0	223	230	230	223	241	228
1.00	1.2	3000	65.0	10.0	10.0	234	248	248	234	252	250
1.50	.2	3000	86.0	10.0	10.0	230	261	259	230	264	259
2.00	.2	3000	85.0	10.0	10.0	261	304	298	261	307	298
2.25	.5	3000	98.0	10.0	10.0	253	309	306	253	313	307
2.50	.5	3000	101.0	10.0	10.0	270	334	327	270	336	329
2.75	.5	3000	107.0	10.0	10.0	282	354	345	282	358	349
3.00	.5	3000	111.0	10.0	10.0	273	360	351	273	361	354
3.25	.2	3000	118.0	10.0	10.0	262	365	354	262	365	360

Both cages broke after 3 minutes at 3.5E6 DN.
"L" type design aluminum cage, type 5052-H32.

RUN NØ 10

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 82	73 - 83
CUP NØ.	73 - 20	73 - 37
CAGE DESIGN	AE / AG	AE / AG
PØST TEST CØNDITIØN	ØK	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	ØIL FLØW (PT/MIN) LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
3.50	2.0	3000	98.0	10.0	10.0	270	383	365	270	379	370
3.50	4.0	3000	127.0	10.0	10.0	253	374	356	253	370	361
3.50	4.0	3000	115.0	10.0	10.0	237	356	340	237	352	345
3.50	4.0	3000	122.0	10.0	10.0	253	370	352	253	367	360
3.50	4.0	3000	119.0	10.0	10.0	241	358	342	241	356	351
3.50	4.0	3000	113.0	10.0	10.0	244	360	343	244	360	347
3.50	4.0	3000	127.0	10.0	10.0	255	370	352	255	369	356

26 Hours at 3.5E6 DN.

R U N N Ø 0

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	73 - 82	73 - 83
CUP NØ.	73 - 20	73 - 37
CAGE DESIGN	AB / FN	AB / FN
PØST TEST CØNDITIØN	CAGE DAMAGE	CAGE DAMAGE

"L" type 4340 steel cages that were Ferritic-Nitrocarburized by Nemo Heat Treatments Limited, England. This is a surface treatment which forms an epsilon iron carbonitride layer which has resistance to scuffing, seizure and surface fatigue. Both cages cracked when they were closed in before testing.

[redacted]

R U N N Ø 11

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 24	76 - 31
CUP NØ.	76 - 4	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

Drive end Rib/Roller end damage after 25 minutes at 3.5E6 DN.

R U N N Ø 12

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 7	76 - 31
CUP NØ.	76 - 4	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

Drive end Rib/Roller end damage accelerating to 3.5E6 DN.

R U N N Ø 13

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 2	76 - 31
CUP NØ.	76 - 4	76 - 5
CAGE DESIGN	AE / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

Drive end Rib/Roller end damage at 2.5E6 DN.

R U N N Ø 14

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 4	76 - 31
CUP NØ.	76 - 4	76 - 5
CAGE DESIGN	AE / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	ØUT	CUP	ØDE IN	ØUT	CUP
3.50	1.5	3000	121.0	10.0	10.0	228	354	342	228	354	340

R U N N Ø 15

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 27	76 - 31
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

Rib/Roller end damage accelerating to 3.5E6 DN.

RUN NØ 16

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 6	76 - 31
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	ØK	ØK

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	DE ØUT	DE CUP	ØDE IN	ØDE ØUT	ØDE CUP
.50	.2	3000	39.0	10.0	10.0	163	165	162	163	167	160
.75	.2	3000	48.0	10.0	10.0	176	187	183	176	187	183
1.00	.2	3000	69.0	10.0	10.0	160	183	183	160	185	183
1.50	.5	3000	79.0	10.0	10.0	181	221	216	181	219	216
2.00	.2	3000	82.0	10.0	10.0	183	246	241	183	243	239
2.25	.5	3000	84.0	10.0	10.0	207	275	268	207	271	268
2.50	.5	3000	91.0	10.0	10.0	196	282	275	196	279	273
2.75	.5	3000	90.0	10.0	10.0	207	302	293	207	298	291
3.25	.5	3000	97.0	10.0	10.0	212	318	307	212	315	306
3.50	4.0	3000	94.0	10.0	10.0	244	369	354	244	365	352
3.50	4.0	3000	99.0	10.0	10.0	237	365	351	237	360	347
3.50	4.0	3000	98.0	10.0	10.0	235	361	349	235	358	345
3.50	4.0	3000	97.0	10.0	10.0	237	361	349	237	358	345
3.50	4.0	3000	99.0	10.0	10.0	237	361	349	237	356	345
3.50	4.0	3000	99.0	10.0	10.0	239	363	351	239	360	347
3.50	4.0	3000	99.0	10.0	10.0	277	392	378	277	388	374
3.50	4.0	3000	100.0	10.0	10.0	293	405	390	293	401	387

32 Hours at 3.5E6 DN.

R U N N Ø 17

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 6	76 - 31
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	ØK	RIB DAMAGE

Rib/Roller end damage after 4 minutes at 3.5E6 DN.

R U N N Ø 18

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 6	76 - 8
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	ØK	ØK

SPEED	TIME	THRUST	AVG. TØRQUE	ØIL FLØW (PT/MIN)		MAX. TEMPERATURE (F) DE			ØDE		
DN*10E-6	HRS.	LBF.	IN-LB	SE	LE	IN	ØUT	CUP	IN	ØUT	CUP
.75	.5	3000	41.0	10.0	10.0	187	187	180	187	190	180
1.00	.2	3000	61.0	10.0	10.0	178	190	187	178	192	189
1.50	.2	3000	76.0	10.0	10.0	199	235	232	199	237	234
2.00	.2	3000	79.0	10.0	10.0	230	280	273	230	282	277
2.25	.5	3000	90.0	10.0	10.0	232	295	289	232	297	291
2.50	.5	3000	91.0	10.0	10.0	241	313	306	241	313	309
2.75	.5	3000	95.0	10.0	10.0	243	329	322	243	327	322
3.00	.5	3000	95.0	10.0	10.0	246	342	333	246	338	334
3.25	.2	3000	98.0	10.0	10.0	253	361	351	253	356	351
3.50	4.0	3000	102.0	10.0	10.0	277	394	381	277	388	381
3.50	4.0	3000	106.0	10.0	10.0	268	387	374	268	381	374
3.50	4.0	3000	105.0	10.0	10.0	268	387	374	268	381	374
3.50	4.0	3000	107.0	10.0	10.0	270	388	376	270	383	376
3.50	4.0	3000	104.0	10.0	10.0	275	394	379	275	388	381
3.50	4.0	3000	98.0	10.0	10.0	282	399	387	282	396	387
3.50	4.0	3000	98.0	10.0	10.0	293	408	396	293	403	396

28 Hours at 3.5E6 DN.

RUN NØ 19

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 9	76 - 10
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	ØK	RIB DAMAGE

SPEED DN*10E-6	TIME HRS.	THRUST LBF.	AVG. TØRQUE IN-LB	ØIL FLØW (PT/MIN) SE	LE	MAX. TEMPERATURE (F) DE IN	ØUT	CUP	ØDE IN	ØUT	CUP
.50	.5	3000	46.0	10.0	10.0	183	-	178	183	185	-
1.00	.2	3000	74.0	10.0	10.0	181	-	203	181	205	-
1.50	.2	3000	88.0	10.0	10.0	199	-	232	199	235	-
2.00	.2	3000	88.0	10.0	10.0	230	-	275	230	280	-
2.25	.5	3000	104.0	10.0	10.0	232	-	288	232	295	-
2.50	.5	3000	103.0	10.0	10.0	250	-	315	250	322	-
2.75	.5	3000	113.0	10.0	10.0	235	-	315	235	322	-
3.00	.5	3000	117.0	10.0	10.0	243	-	331	243	340	-
3.25	.2	3000	122.0	10.0	10.0	252	-	349	252	360	-
3.50	4.0	3000	128.0	10.0	10.0	286	-	390	286	405	392
3.50	4.0	3000	127.0	10.0	10.0	289	-	392	289	406	394
3.50	4.0	3000	128.0	10.0	10.0	288	-	388	288	405	392
3.50	4.0	3000	126.0	10.0	10.0	289	-	390	289	405	392
3.50	4.0	3000	127.0	10.0	10.0	289	-	392	289	406	394
3.50	4.0	3000	126.0	10.0	10.0	293	-	396	293	410	397
3.50	24.0	3000	134.0	10.0	10.0	280	-	385	280	399	387
3.50	24.0	3000	137.0	10.0	10.0	280	-	387	280	401	388
3.50	9.0	3000	132.0	10.0	10.0	280	-	390	280	403	388

81 Hours at 3.5E6 DN. Debris filled the manifold and caused an uneven distribution of oil. Both cones had reground revised manifolds.

R U N N Ø 20

	DE PØSITIØN	ØDE PØSITIØN
CØNE NØ.	76 - 9	76 - 8
CUP NØ.	76 - 1	76 - 5
CAGE DESIGN	AF / AG	AF / AG
PØST TEST CØNDITIØN	RIB DAMAGE	ØK

Drive end Rib/Roller end damage at 3.0E6 DN. Debris found in drive end manifold that caused an uneven distribution of oil.

RUN

TASK3 27-0CT-77 08:15

APPENDIX B

BEARING HEAT GENERATION TEST DATA

ØIL FLØW DISTRIBUTIØN
10 PT/MIN S E
10 PT/MIN L E

NØ.	* CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
1	AF	2512	973	40.4	209	210	20	33	17	21
2	AF	2512	1002	40.3	210	210	19	33	12	21
3	AF	2512	998	40.2	210	211	19	32	28	21
4	AF	2512	999	40.2	211	212	19	32	28	21
5	AF	2512	3007	40.2	210	213	26	44	47	29
6	AF	2512	3002	40.2	210	213	26	44	47	29
7	AF	2512	3002	40.1	211	213	26	44	45	29
8	AF	2512	3001	40.2	210	212	26	44	48	29
9	AF	2512	3013	40.2	211	213	26	44	45	29
10	AF	2512	2996	40.1	210	212	25	43	48	29
11	AF	2512	5994	40.1	210	213	33	56	59	35
12	AF	2512	5991	40.2	210	213	33	56	60	35
13	AF	2512	6003	40.2	210	213	33	55	55	35
14	AF	2512	6004	40.2	210	213	33	56	59	35
15	AF	2512	6005	40.2	210	213	33	55	62	35
16	AF	9257	1041	39.9	209	225	49	304	298	43
17	AF	9257	1019	39.9	209	225	49	303	298	43
18	AF	9257	1007	40.0	209	225	49	305	300	43
19	AF	9257	3044	39.0	211	227	60	374	298	59
20	AF	9257	3006	40.0	212	230	61	381	337	58

NOTE: Load in lbf., Flow in pt./min., and Torque in lb·in

* Cage Part Number Suffix: AE - Roller Guided, S-Type Cage
AF - Race Guided, Z-Type Cage

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
21	AF	9257	3009	39.9	209	228	64	396	369	58
22	AF	9257	3016	39.9	210	229	61	378	368	58
23	AF	9257	6067	39.9	213	234	74	461	412	70
24	AF	9257	6008	40.0	209	232	74	462	445	70
25	AF	9257	5992	40.0	209	232	75	469	450	70
26	AF	9257	5975	39.9	209	232	75	466	448	70
27	AF	9257	5979	39.9	209	233	75	465	446	70
28	AF	20813	1025	40.5	204	261	82	1142	1103	59
29	AF	20782	1025	40.0	208	264	81	1127	1092	58
30	AF	20828	1034	40.0	209	265	80	1124	1092	58
31	AF	20828	3003	39.7	206	277	97	1360	1372	75
32	AF	20828	3003	39.7	209	279	96	1350	1349	75
33	AF	20828	3017	39.8	209	279	97	1358	1353	75
34	AF	20828	3001	39.7	209	279	97	1365	1353	75
35	AF	20782	3001	39.8	210	280	97	1354	1351	74
36	AF	20813	3006	39.7	210	280	97	1361	1345	74
37	AF	20782	6057	39.5	211	290	108	1512	1515	88
38	AF	20828	6039	40.4	211	289	110	1539	1535	88
39	AF	20797	6011	40.4	210	288	110	1533	1546	88
40	AF	20843	6010	40.4	210	288	110	1544	1548	88

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
41	AF	32475	3009	39.8	215	346	117	2560	2592	76
42	AF	32429	3005	40.0	222	352	119	2597	2583	75
43	AF	32475	3009	40.5	225	355	120	2619	2593	74
44	AF	32429	6004	39.8	230	372	131	2864	2800	87
45	AF	2375	1002	39.9	300	301	15	25	21	13
46	AF	2314	1004	39.9	300	301	15	24	26	13
47	AF	2329	2995	40.0	299	300	20	31	12	18
48	AF	2314	3008	40.0	301	302	20	30	19	17
49	AF	2329	6011	40.2	295	295	29	45	-5	22
50	AF	2329	5991	40.1	299	299	29	45	3	22
51	AF	9287	1014	40.5	300	310	38	237	200	29
52	AF	9302	1027	40.4	301	312	40	248	208	29
53	AF	9272	3022	40.4	300	313	52	323	268	39
54	AF	9272	3004	40.5	300	314	50	313	272	39
55	AF	9226	6010	40.3	299	316	57	351	321	48
56	AF	9165	6002	40.3	301	316	57	355	308	48
57	AF	9181	6002	40.3	300	317	58	359	324	47
58	AF	9181	5996	40.3	301	317	59	366	315	47
[illegible]	AF	[illegible]	[illegible]	[illegible]	[illegible]	315	78	1091	974	47
[illegible]	AF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	73	1050	[illegible]	46

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
61	AF	20828	3025	40.4	273	331	95	1329	1147	61
62	AF	20828	3017	40.4	281	337	91	1274	1101	60
63	AF	20858	3014	40.3	288	343	91	1271	1078	59
64	AF	20797	6002	40.2	304	360	94	1313	1104	68
65	AF	20767	5999	41.3	299	355	99	1390	1133	69
66	AF	20828	6014	40.3	285	347	102	1432	1206	71
67	AF	20858	6018	40.4	311	368	99	1383	1117	67
68	AF	32444	3014	39.9	287	404	112	2445	2314	65
69	AF	32460	3009	40.7	292	407	114	2486	2319	64
70	AF	32460	3027	40.7	298	412	112	2448	2285	64
71	AF	32460	3014	40.7	298	412	114	2492	2291	63
72	AF	32475	3013	40.7	299	413	113	2478	2297	63
73	AF	32414	4504	40.9	287	404	144	3144	2362	73
74	AF	32444	4503	40.3	295	412	143	3132	2336	72
75	AF	32444	4487	40.2	301	418	142	3097	2324	71
76	AF	32444	4494	40.1	302	419	141	3075	2321	70

LINE 600-ØUT ØF DATA

C/P UNITS 23

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*RUN

TASK31 27-ØCT-77 08:29

ØIL FLØW DISTRIBUTIØN
8 PT/MIN S E
12 PT/MIN L E

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
1	AF	2269	981	40.4	206	205	19	29	-26	20
2	AF	2269	1007	40.3	211	210	19	29	-17	20
3	AF	2314	3004	40.1	210	211	30	46	21	27
4	AF	2299	3001	40.5	212	214	29	45	42	27
5	AF	2299	3032	40.3	209	211	29	44	38	27
6	AF	2269	6011	40.1	208	212	44	68	88	33
7	AF	2314	6002	40.2	209	214	40	63	78	33
8	AF	9287	964	40.1	212	227	47	293	289	42
9	AF	9272	1065	39.9	205	221	50	315	313	45
10	AF	9333	1011	39.8	215	231	48	299	304	42
11	AF	9348	1013	40.5	213	229	47	298	316	42
12	AF	9257	3019	40.2	215	235	56	347	375	56
13	AF	9257	3068	40.2	211	231	59	368	378	58
14	AF	9226	2989	40.2	214	234	56	349	378	56
15	AF	9287	6015	40.0	207	232	67	421	481	71
16	AF	9257	6011	40.4	207	231	65	406	471	71
17	AF	20965	1010	40.4	211	265	74	1049	1073	58
18	AF	21011	1016	40.4	211	267	75	1064	1085	57
19	AF	21011	2978	40.1	212	278	90	1270	1276	75
20	AF	20752	2998	40.2	210	276	90	1256	1282	75

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
21	AF	20797	2987	39.9	211	275	91	1267	1234	76
22	AF	20752	2979	40.1	213	276	90	1260	1244	75
23	AF	20813	2967	40.3	210	275	89	1253	1273	76
24	AF	20797	6016	40.3	210	282	98	1373	1416	91
25	AF	20782	6009	40.2	211	283	97	1355	1418	90
26	AF	20797	6015	40.3	211	284	96	1345	1420	90
27	AF	20691	6010	40.6	211	285	100	1397	1464	89
28	AF	20797	6010	40.7	209	284	101	1411	1480	90
29	AF	32414	3015	39.9	232	355	129	2820	2429	74
30	AF	32323	3023	40.3	240	362	130	2819	2425	73
31	AF	32460	3028	40.4	242	363	128	2802	2414	73
32	AF	32414	4505	40.3	242	369	133	2912	2542	80
33	AF	32414	4508	40.4	243	370	135	2940	2533	80
34	AF	32414	4512	40.4	250	375	134	2912	2501	79
35	AF	2284	1008	40.1	293	292	13	19	-3	13
36	AF	2299	993	40.2	297	297	12	19		13
37	AF	2314	978	40.1	299	300	11	17	3	13
38	AF	2329	3017	40.2	298	300	20	31	31	18
39	AF	2329	3001	40.1	301	303	19	30	35	17
40	AF	2314	3075	40.0	303	304	20	31	17	17

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
41	AF	2314	6046	40.3	300	303	30	47	58	21
42	AF	2314	5990	40.3	301	304	28	44	65	21
43	AF	2329	5950	40.3	299	303	28	44	66	21
44	AF	2177	5957	40.3	299	303	28	40	70	21
45	AF	2360	5967	40.3	299	302	28	44	70	22
46	AF	9211	1015	40.3	296	311	47	289	274	29
47	AF	9211	1070	40.4	303	316	45	282	244	29
48	AF	9196	1051	40.5	298	311	47	293	260	29
49	AF	9150	3023	40.9	304	318	52	318	290	38
50	AF	9242	2996	40.1	298	314	53	328	303	39
51	AF	9165	6043	40.2	296	313	57	353	322	48
52	AF	9165	5949	40.1	301	318	57	352	329	47
53	AF	9150	6001	40.1	301	318	56	348	329	47
54	AF	20752	1043	40.3	301	343	67	933	823	43
55	AF	20767	1043	40.4	306	348	66	924	818	42
56	AF	20767	978	40.0	292	339	66	922	913	42
57	AF	20858	3028	40.6	292	344	79	1116	1015	59
58	AF	20767	3033	40.4	307	355	79	1105	956	56
59	AF	20782	6050	40.1	293	351	90	1254	1134	70
60	AF	20873	6043	40.3	295	353	89	1256	1147	70

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
61	AF	20813	6028	40.1	303	359	95	1329	1103	69
62	AF	20828	5968	40.2	288	349	99	1393	1211	70
63	AF	20858	5980	40.6	291	352	97	1366	1206	70
64	AF	20813	5942	40.1	288	355	98	1371	1312	69
65	AF	32505	3013	40.2	298	410	101	2215	2223	64
66	AF	32505	3018	40.3	298	411	104	2272	2241	64
67	AF	32505	3009	40.4	299	411	105	2288	2228	64
68	AF	32505	3012	40.5	298	410	103	2249	2232	64
69	AF	32475	4523	40.3	300	417	107	2348	2327	71
70	AF	32490	4520	40.4	299	416	109	2379	2342	71
71	AF	32490	4516	40.0	298	416	107	2349	2334	71

LINE 600-ØUT ØF DATA

C/P UNITS 21

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RUN

TASK32 27-ØCT-77 08:42

ØIL FLØW DISTRIBUTIØN
12 PT/MIN S E
8 PT/MIN L E

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
1	AF	2314	975	40.3	208	206	21	33	-41	20
2	AF	2299	1020	40.1	210	209	20	32	-27	20
3	AF	2314	1026	40.0	211	211	21	33	-10	20
4	AF	2451	2997	40.6	208	210	31	51	37	29
5	AF	2299	3002	40.4	210	212	30	47	31	27
6	AF	2314	3005	40.4	211	212	30	47	33	27
7	AF	2284	2998	40.4	211	212	30	46	31	27
8	AF	2329	6007	40.4	208	211	41	65	61	34
9	AF	2314	6009	40.4	210	213	40	62	59	33
10	AF	2284	6009	40.3	211	214	39	60	62	33
11	AF	9363	1013	40.3	209	226	51	322	326	43
12	AF	9333	1016	40.3	208	225	52	326	327	43
13	AF	9348	1021	40.3	209	225	52	326	323	43
14	AF	9272	2996	40.3	210	230	63	390	390	58
15	AF	9363	2980	40.2	210	231	63	397	391	58
16	AF	9333	2987	40.3	211	232	62	388	393	58
17	AF	9226	5988	40.1	209	232	75	464	435	70
18	AF	9287	5968	40.0	210	233	74	460	446	70
19	AF	9302	5951	40.4	209	232	74	464	452	70
20	AF	20706	1029	40.5	209	265	76	1066	1099	57

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
21	AF	20782	1002	40.3	209	265	76	1057	1101	57
22	AF	20782	1003	40.4	209	265	76	1063	1105	57
23	AF	20782	962	40.3	203	262	79	1109	1154	57
24	AF	20813	977	40.4	204	261	79	1112	1111	58
25	AF	20767	977	40.4	206	262	78	1093	1108	58
26	AF	20752	3051	40.3	208	277	95	1322	1368	75
27	AF	20858	2967	40.1	213	281	92	1298	1330	74
28	AF	20782	2948	40.0	211	280	93	1300	1338	74
29	AF	20813	2980	40.3	211	279	94	1315	1348	74
30	AF	20813	2998	40.1	210	277	94	1314	1307	75
31	AF	20965	2988	40.1	209	277	95	1344	1323	75
32	AF	20782	3013	40.2	208	277	95	1324	1336	75
33	AF	20813	6013	40.4	212	286	106	1488	1459	89
34	AF	20797	6037	40.6	211	286	109	1525	1481	89
35	AF	20934	6012	40.4	208	284	109	1538	1502	90
36	AF	32444	3040	39.3	222	351	119	2594	2497	75
37	AF	32582	3031	38.9	232	360	117	2576	2466	73
38	AF	32475	3032	40.2	238	363	120	2613	2473	73
39	AF	32566	4529	40.3	242	372	127	2780	2592	80
40	AF	32460	4543	40.2	243	373	128	2806	2589	80

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
41	AF	2406	1039	40.2	297	295	14	23	-35	13
42	AF	2329	996	40.1	302	300	14	22	-30	13
43	AF	2314	3026	40.3	300	300	20	32	-3	18
44	AF	2543	3016	42.1	302	302	21	35	7	18
45	AF	2284	3041	40.4	300	301	21	32	14	17
46	AF	2284	6003	40.4	302	302	28	43	2	21
47	AF	2360	5997	40.4	302	303	27	43	32	22
48	AF	2177	6031	40.5	304	305	28	41	19	20
49	AF	9394	1009	40.3	300	312	41	256	226	29
50	AF	9409	1003	40.3	300	311	40	254	222	29
51	AF	9287	994	40.3	300	311	40	248	221	29
52	AF	9257	3019	40.5	298	312	50	309	274	39
53	AF	9348	3025	40.6	298	312	49	311	282	40
54	AF	9379	3025	40.5	298	312	49	310	282	40
55	AF	9409	3029	40.3	298	312	49	310	283	40
56	AF	9333	5946	40.5	299	315	55	344	310	48
57	AF	9287	5995	40.5	299	315	57	353	307	48
58	AF	9348	5997	40.5	299	316	57	357	316	48
59	AF	20858	1007	40.1	286	331	71	994	866	44
60	AF	20873	1003	40.3	290	335	71	999	868	43

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
61	AF	20828	996	40.2	293	337	71	995	859	43
62	AF	20797	1004	40.1	288	331	69	969	835	44
63	AF	20752	1013	40.1	295	336	68	955	805	43
64	AF	20767	996	40.0	296	338	68	946	815	43
65	AF	20858	3000	40.3	294	348	86	1205	1057	58
66	AF	20873	3050	40.3	308	359	85	1201	996	56
67	AF	20752	3054	40.3	300	351	85	1184	1012	57
68	AF	20752	3000	40.4	303	353	83	1160	988	57
69	AF	20797	5912	39.8	295	357	89	1245	1189	69
70	AF	20782	6024	40.2	286	346	96	1340	1187	71
71	AF	20752	6036	40.1	298	357	95	1329	1145	69
72	AF	20767	6040	40.2	291	350	93	1298	1159	71
73	AF	20767	6027	40.1	307	361	90	1257	1064	68
74	AF	32475	3016	40.3	291	401	102	2234	2191	65
75	AF	32444	2961	39.8	294	407	102	2221	2224	64
76	AF	32505	3007	40.4	300	412	103	2261	2224	64
77	AF	32490	4526	40.4	295	416	111	2429	2412	71
78	AF	32475	4531	40.6	301	420	110	2394	2383	71
79	AF	32490	4526	40.5	300	420	109	2375	2394	70

LINE 400-OUT OF DATA

C/F UNITS 33

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RUN

TASK33 27-ØCT-77 09:51

ØIL FLØW DISTRIBUTIØN
10 PT/MIN S E
10 PT/MIN L E

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
1	AE	2345	1000	40.1	205	204	21	33	-22	22
2	AE	2269	998	40.1	210	210	21	33	-9	20
3	AE	2238	1033	40.4	207	208	22	33	7	21
4	AE	2329	3015	40.4	207	210	38	59	54	29
5	AE	2512	3076	40.3	214	216	36	60	43	29
6	AE	2345	3000	40.4	210	213	35	55	54	28
7	AE	2451	2991	40.5	210	213	34	56	56	29
8	AE	2329	6002	40.3	209	206	44	69	-55	36
9	AE	2360	6011	40.3	210	208	44	70	-28	36
10	AE	2314	6013	40.2	209	209	44	69	7	36
11	AE	9287	1009	40.3	210	226	51	320	318	44
12	AE	9318	1010	40.3	209	225	51	320	321	45
13	AE	9287	1011	40.2	209	225	51	318	319	45
14	AE	9211	3005	40.2	208	230	67	414	420	60
15	AE	9257	3031	40.2	209	231	67	415	415	60
16	AE	9287	3034	40.2	209	230	65	409	411	60
17	AE	9242	5966	40.2	212	238	81	505	504	71
18	AE	9242	5974	40.2	209	236	81	505	504	71
19	AE	9287	5998	40.3	209	235	80	500	493	72
20	AE	20767	1021	40.3	209	265	83	1165	1089	60

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL TEMP.(F.) T-IN	T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
21	AE	20904	993	40.4	211	267	84	1181	1089	59
22	AE	20828	1016	40.3	212	268	84	1183	1101	59
23	AE	20797	3001	40.2	213	280	103	1442	1326	77
24	AE	20767	2997	40.5	210	279	104	1453	1350	77
25	AE	20797	5979	40.5	213	290	117	1637	1518	91
26	AE	20782	6017	40.3	213	290	118	1654	1514	91
27	AE	2269	1015	40.7	294	296	14	21	40	13
28	AE	2345	1000	40.5	297	300	13	20	51	13
29	AE	2238	1017	40.5	298	300	13	19	30	13
30	AE	2314	1008	40.9	299	301	15	23	35	13
31	AE	2329	1005	40.9	298	300	15	23	44	13
32	AE	2329	1024	41.0	299	301	15	23	35	13
33	AE	2253	3011	40.4	299	301	27	41	49	18
34	AE	2360	2995	40.4	299	302	26	41	44	18
35	AE	2284	3004	40.4	300	302	24	37	42	18
36	AE	2360	3040	41.0	299	302	20	32	46	18
37	AE	2345	3041	40.9	299	302	21	33	46	18
38	AE	2360	3039	40.9	299	301	21	33	43	18
39	AE	2253	6024	40.4	299	303	42	64	82	22
40	AE	2299	6015	40.4	299	304	38	59	82	22

				ØIL	ØIL TEMP.(F.)		MEASURED	HEAT(BTU/MIN)		CAL.
NØ.	CAGE	RPM	LØAD	FLØW	T-IN	T-ØUT	TØRQUE	Q-BRG	Q-ØIL	TØRQUE
41	AE	2314	6015	40.4	300	303	36	56	63	22
42	AE	2329	6020	41.3	300	303	30	47	54	22
43	AE	2360	6019	40.9	301	304	30	48	58	22
44	AE	2314	5999	40.9	299	302	30	47	62	22
45	AE	9257	1024	40.7	300	312	41	257	233	30
46	AE	9226	1027	40.7	299	311	40	247	235	30
47	AE	9242	1030	40.7	299	311	40	247	237	30
48	AE	9226	1034	40.7	299	311	40	246	233	30
49	AE	9363	3042	40.7	299	315	51	321	300	41
50	AE	9226	3031	40.6	299	314	49	306	291	41
51	AE	9257	3025	40.7	300	314	50	311	284	41
52	AE	9302	6036	40.8	298	316	59	371	351	50
53	AE	9302	6019	40.6	299	317	59	366	344	50
54	AE	9272	6011	40.6	300	317	59	365	342	50
55	AE	20873	1012	40.0	299	343	66	925	844	44
56	AE	20767	1012	40.8	295	341	66	927	902	44
57	AE	20782	1012	40.7	300	344	64	899	887	44
58	AE	20813	3015	40.4	298	347	81	1134	1099	60
59	AE	20736	3005	40.5	296	350	80	1123	1069	59
60	AE	20704	3009	40.7	304	357	76	1107	1019	58

NØ.	CAGE	RPM	LØAD	ØIL FLØW	ØIL T-IN	TEMP.(F.) T-ØUT	MEASURED TØRQUE	HEAT(BTU/MIN) Q-BRG	Q-ØIL	CAL. TØRQUE
61	AE	20782	6030	40.9	292	351	94	1312	1170	73
62	AE	20767	6022	40.5	295	353	91	1269	1156	72
63	AE	20767	6027	40.7	310	366	88	1230	1112	70
64	AE	32368	3001	40.7	293	404	110	2400	2213	67
65	AE	32368	2989	40.4	300	410	110	2402	2192	66
66	AE	32414	3026	40.3	295	407	112	2450	2233	67

LINE 600-ØUT ØF DATA

C/P UNITS 21
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AD-A054 045 TIMKEN CO CANTON OHIO F/G 13/9
TAPERED ROLLER BEARING DEVELOPMENT FOR AIRCRAFT TURBINE ENGINES--ETC(U)
DEC 77 P S ORVOS, G J DRESSLER F33615-76-C-2019

UNCLASSIFIED AFAPL-TR-77-83 NL

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REFERENCES

1. Cornish, R. F., Orvos, P. S., and Dressler, G. J., "Design, Development and Testing of High Speed Tapered Roller Bearings for Turbine Engines," Technical Report AFAPL-TR-75-26, The Timken Company, July 1975.

2. Orvos, P. S., "Tapered Roller Bearing Development for Aircraft Turbine Engines," Technical Report AFAPL-TR-77-6, The Timken Company, March 1977.

3. Witte, D. C., "Operating Torque of Tapered Roller Bearings," Presented at ASME-ASLE International Lubrication Conference, New York City, October 9-12, 1972.

4. Parker, R. J., and Signer, H. R., "Lubrication of High Speed, Large Bore Taper-Roller Bearings," Presented at ASLE-ASME Joint Lubrication Conference, Kansas City, Missouri, October 3-5, 1977.

5. Leibensperger, R. L., "An Analysis of the Flow of Oil Through a Tapered Roller Bearing," Presented at the ASLE-ASME Joint Lubrication Conference, Pittsburgh, Pennsylvania, October 5-7, 1971.

6. Moyer, C. A. and Wren, F. J., "Understanding Friction and EHL Films in Concentrated Contacts of a Tapered Roller Bearing," EHL Symposium, Leeds, England, 1972.

☆U.S.Government Printing Office: 1978 — 757-080/425